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FACULTAD DE GEOGRAFÍA E HISTORIA
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TESIS DOCTORAL

Land use and land cover on the Macaronesian islands of Portugal and Spain: new methods for quantifying and visualizing information from spatial patterns

Uso y cobertura del suelo en las islas macaronésicas de Portugal y España: nuevos métodos para cuantificar y visualizar información de patrones espaciales

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Trabajo de investigación que presenta

Michael Richard Barros Rodrigues

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Table of contents

List of tables

List of appendix figures

List of abbreviations and acronyms

ASL: Above Sea Level

AZRC: Altitudinal Zonation Radial Chart

CLC: CORINE Land Cover

CLC1990: CORINE Land Cover for the year 1990

CLC2000: CORINE Land Cover for the year 2000

CLC2006: CORINE Land Cover for the year 2006

CORINE: Coordinated Information on the European Environment

CZC: Coastal Zonation Chart

EEA: European Environmental Agency

ENE: East-Northeast

ESE: East-Southeast

EU: European Union

EUROSTAT: Statistical Office of the European Communities

GDMED2: Global Digital Elevation Model version 2

GIS: Geographic Information Science

ICZM: Integrated Coastal Zone Management

LULC: Land Use and Land Cover

M: Million

Ma: Million years

MSA: Morphological Settlement Area

NNE: North-Northeast

NNW: North-Northwest

SSE: South-Southeast

SSW: South-Southwest

WSW: West-Southwest

WNW: West-Northwest

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Resumen

El objetivo principal de esta investigación es proponer nuevos métodos para cuantificar y visualizar información geográfica, con el fin de facilitar el proceso de toma de decisiones en relación a los patrones de uso y ocupación del suelo. De este modo, se desarrollan y aplican varios métodos de modelación y visualización geográfica, utilizando las islas macaronésicas de Portugal y España como áreas de estudio. La Macaronesia es una región biogeográfica que integra varios archipiélagos en el Océano Atlántico pertenecientes a tres países: Portugal, España y Cabo Verde. Esta investigación abarca tres archipiélagos: Azores, Madeira y Canarias. Para una evaluación detallada de uso y cobertura del suelo se seleccionaron las cuatro islas más densamente pobladas: San Miguel, Madeira, Tenerife y Gran Canaria.

Una característica común a las islas macaronésicas es que, desde de la colonización en el siglo XV hasta mediados del siglo XX, el cambio antropogénico del suelo se debió principalmente a las actividades agrícolas, que ocuparon bosques y áreas naturales. A mediados del siglo XX, debido a profundos cambios sociales y económicos, el sector terciario empezó su ascenso para convertirse en el principal sector económico. Debido a que el sector secundario en esta región siempre ha tenido una importancia menor, este proceso de terciarización de la economía supuso un progresivo abandono del sector primario. Por lo tanto, las áreas agrícolas comenzaron a experimentar un claro retroceso. Como resultado de este proceso, las últimas décadas del siglo XX se caracterizaron por un cambio significativo en las dinámicas de uso y cobertura del suelo. Las actividades agrícolas dejaron de ser la principal fuerza impulsora en el cambio de lo suelo y fueron reemplazadas por el aumento desenfrenado de las superficies artificiales, principalmente en las zonas costeras del sur, donde el turismo y la especulación inmobiliaria ejercen una gran presión sobre el paisaje. Consecuencia directa de esta presión fueron las drásticas transformaciones de los paisajes costeros de las islas.

A través de los tres primeros objetivos de la investigación, esta tesis propone tres nuevos métodos estáticos 2D basados en gráficos para la representación de datos geoespaciales. Estos nuevos métodos proporcionan un marco para estudiar y representar datos geoespaciales multivariados, a través de una representación de la información en gráficos diseñados al efecto. Los métodos proponen sustituir los datos geoespaciales originales por una representación gráfica indirecta de esos datos de cara a resumir la información. De esta forma es posible representar simultáneamente datos multivariados en una sola presentación gráfica. Los métodos son flexibles, espacialmente explícitos, y adecuados para ser aplicados a cualquier región. La representación gráfica de los datos de uso y cobertura del suelo a través de los métodos propuestos permite realizar una evaluación temporal del paisaje. Los resultados

obtenidos al aplicar estos métodos han puesto de manifiesto que la dinámica actual de uso y cobertura del suelo más significativa en las islas es el notable incremento de las superficies artificiales.

Los dos últimos objetivos de la investigación se refieren al desarrollo de métodos de modelización espacial basados en SIG. Así, el cuarto objetivo propone una novedosa técnica de modelado, en el que se utiliza el cambio de uso/cobertura del suelo a y entre superficies artificiales como una aproximación a la presión sobre el desarrollo del suelo. Los resultados demuestran que este nuevo método de modelización espacial conduce a la identificación de áreas que han estado sometidas a la presión urbanizadora, uno de los principales procesos espaciales antropogénicos que influyen en el desarrollo sostenible.

A lo largo de la tesis, a partir de cinco preguntas de investigación se caracterizan y cuantifican los patrones y tendencias generales del uso y la cobertura del suelo en las islas macaronésicas de Portugal y España. Es importante señalar que en estas islas los datos geoespaciales disponibles no se ajustan a la necesidad de disponer de datos europeos en diferentes niveles territoriales en una perspectiva trans-regional y transfronteriza. Dado que los únicos datos comparables de uso y cobertura del suelo disponibles para el área de estudio son los datos de "CORINE Land Cover", en esta investigación se procedió a elaborar una cartografía de alta resolución de los asentamientos de las cuatro principales islas a través de la clasificación e interpretación de imágenes aéreas. Esta cartografía fue utilizada, en el marco del quinto y último objetivo de la investigación, para proponer una nueva clasificación tipológica de los patrones de asentamientos y verificar la hipótesis de que las variables topográficas ejercen una influencia estadísticamente significativa sobre la tipología de los asentamientos en estas islas.

En conclusión, esta tesis proporciona una contribución innovadora y original a los sistemas de ayuda a la toma de decisiones espaciales en relación al uso y la cobertura del suelo. El enfoque elegido se basa en proponer nuevos métodos de modelación y representación geográfica, destacando la importancia de la visualización geográfica para la ordenación del territorio.

Palabras clave: uso del suelo; cobertura del suelo; cambios en el uso/cobertura del suelo; geovisualización; patrones espaciales; Macaronesia.

Resumo

Esta investigação tem como principal objectivo propor novos métodos para quantificar e visualizar informação geográfica, de modo a auxiliar o processo de tomada de decisão quando seja necessário analisar padrões de uso e ocupação do solo. Ao longo da investigação são apresentados vários métodos de modelação e visualização geográfica, usando como área de estudo as ilhas da Macaronésia pertencentes a Portugal e Espanha. A Macaronésia é uma região biogeográfica no Oceano Atlântico constituída por vários arquipélagos pertencentes a três países: Portugal, Espanha e Cabo Verde. Este trabalho de investigação abrange três arquipélagos: os Açores, a Madeira e as Ilhas Canárias. Para uma avaliação mais detalhada quanto ao uso e ocupação do solo, foram seleccionadas as quatro ilhas mais densamente povoadas: São Miguel, Madeira, Gran Canaria e Tenerife.

Uma característica comum às ilhas da Macaronésia reside na particularidade de, desde a sua colonização no século XV, até meados do século XX, as alterações antropogénicas do solo terem estado predominantemente associadas às actividades agrícolas que consumiram extensas áreas de floresta e espaços naturais. Em meados do século XX, devido a profundas alterações sociais e económicas, o sector terciário iniciou a sua ascensão para se tornar o principal sector económico. Uma vez que, nesta região, o sector secundário foi sempre pouco significativo, a terciarização da actividade económica ditou um progressivo abandono do sector primário. Deste modo, as áreas agrícolas começaram a recuar. Como resultado deste processo, as últimas décadas do século XX foram marcadas por uma mudança significativa na dinâmica de uso e ocupação do solo nas ilhas desta região. As actividades agrícolas deixaram de ser a principal força motriz para as alterações no uso do solo, sendo substituídas pelo aumento galopante das superfícies artificiais, principalmente nas áreas costeiras do sul, onde as actividades relacionadas com o turismo e a especulação imobiliária causaram um grande impacto na paisagem, e contribuiram para a transformação drástica do litoral sotavento das ilhas.

Através dos primeiros três objectivos da investigação, esta tese propõe três novos métodos estáticos 2D baseados em gráficos de modo a representar dados geoespaciais. Ao longo deste trabalho de investigação, os métodos de visualização geográfica propostos fornecem uma estrutura para analisar e representar informação espacial multivariada recorrendo a gráficos personalizados. Nos métodos propostos, os dados geoespaciais são substituídos por uma representação gráfica indirecta desses dados de modo a sintetizar a informação. Isto permite a representação simultânea de informação multivariada numa única apresentação gráfica. Os métodos propostos são flexíveis, espacialmente explícitos, e adequados para serem aplicados a qualquer outra área de estudo. A representação gráfica dos dados de uso e ocupação do solo através das abordagens propostas permite realizar uma avaliação temporal da paisagem. Após a aplicação dos métodos propostos, os resultados revelaram que a dinâmica contemporânea de uso e ocupação do solo nas ilhas está marcada pelo aumento significativo das superfícies artificiais.

Os dois últimos objectivos da investigação são dedicados a metodologias de modelação espacial baseadas em SIG. O quarto objectivo da investigação propõe um novo método de modelação espacial, no qual as alterações do solo entre-e-para superfícies artificiais são usadas como aproximação à pressão de desenvolvimento do solo. Os resultados mostram que esta nova abordagem permite a identificação de áreas que foram sujeitas à pressão de desenvolvimento do solo, um dos principais processos espaciais antropogénicos que influencia o desenvolvimento sustentável.

Ao longo da tese, cinco perguntas de investigação caracterizam e quantificam os principais padrões de uso e ocupação do solo nas ilhas da Macaronésia pertencentes a Portugal e Espanha. É importante ter em conta que, nestas ilhas, as soluções de dados geoespaciais disponíveis não estão em conformidade com a necessidade de dados europeus a diferentes níveis territoriais, numa perspectiva trans-regional e transfronteiriça. Uma vez que os únicos dados comparáveis de uso e ocupação do solo disponíveis para as áreas de estudo são os dados “CORINE Land Cover”, esta investigação procedeu a uma cartografia de alta resolução dos povoamentos das quatro ilhas principais, por meio da classificação e interpretação de imagens aéreas. Ao terminar a investigação, as áreas dos povoamentos foram utilizadas a fim de, no quinto e último objectivo da investigação, propor uma nova classificação tipológica de padrões de povoamento. Esta classificação permite testar a hipótese se a importância das variáveis topográficas é estatisticamente significativa na tipologia de povoamentos destas ilhas.

Em conclusão, esta tese fornece uma contribuição inovadora e original para os sistemas espaciais de apoio à decisão quando seja necessário analisar dados de uso e ocupação do solo. A abordagem escolhida assenta em propor novos métodos de modelação e de representação geográfica, enfatizando a importância que a visualização geográfica tem no planeamento do território.

Palavras-chave: uso do solo; cobertura do solo; alterações no uso/ocupação do solo; geovisualização; padrões espaciais; Macaronésia.

Abstract

The aim of this research is to propose novel methods for quantifying and visualizing geographical information, in order to aid the spatial planning decision-making process when addressing land use and land cover patterns. In doing so, several modeling and geographic visualization methods are developed and demonstrated by using the Macaronesian islands of Portugal and Spain as study areas. Macaronesia is a biogeographical region consisting of several archipelagos in the Atlantic Ocean belonging to three countries: Portugal, Spain, and Cape Verde. This research encompasses three archipelagos: the Azores, Madeira, and the Canary Islands. From these three archipelagos, the four most densely populated islands were further selected for the land use and land cover assessments: São Miguel, Madeira, Tenerife, and Gran Canaria.

A common feature of the Macaronesian islands is that, ever since European colonization in the fifteenth century, up until the mid-twentieth century, anthropogenic land change was predominately attributable to agricultural activities consuming forests and natural areas. In the mid-twentieth century, owing to profound social and economic changes, the tertiary sector started its rise in becoming the main economic sector. Because the secondary sector in this region has always been minor, this substantial shift to the tertiary sector would dictate a progressive abandonment of the primary sector. Hence, agricultural areas started to recede. As a result, the last decades of the twentieth century were marked by a significant shift in land use dynamics. Agricultural activities ceased to be the main driving force of land change and were replaced by a rampant increase of the artificial surfaces, mainly on the southern coastal areas, where tourism-related and real estate pressure constitute a major impact on the landscape. A direct consequence of this pressure was the drastic transformation across the islands' leeward coastal landscapes.

Through the first three research objectives, this research proposes three novel 2D static graph-based methods for representing geospatial data. The proposed methods provide a framework for studying and representing multivariate geospatial data, through a graphical representation of the information in custom-made spatially explicit charts. In the proposed methods, geospatial data is replaced by an indirect, graphical representation of that data in order to summarize the information. This allows a simultaneous representation of multivariate data in a single graphical presentation. The three methods are flexible, spatially explicit and meaningful, and suitable for application elsewhere. The graphical depiction of land use and land cover data through the proposed approaches allows performing a visual temporal assessment of the landscape. After applying the proposed methods, the results have revealed that the most

significant contemporary land use dynamic across the islands is the marked increase of the artificial surfaces.

The last two research objectives are dedicated to GIS-based modeling approaches. One of these research objectives proposes a novel modeling technique in which land change in and into artificial surfaces is used as a proxy of land development pressure. The results demonstrate that this novel GIS-based modeling approach leads to the identification of areas that have been prone to land development pressure, one of the major anthropogenic spatial processes influencing sustainable development.

Throughout the thesis, five research questions characterize and quantify the overall land use/cover patterns and trends in the Macaronesian islands of Portugal and Spain. An important note is that in these islands the existing available geospatial data solutions do not conform to the need for European data on different territorial levels in a trans-regional and trans-border perspective. Because the "CORINE Land Cover" datasets are the only comparable land use and land cover data available for these islands, this research proceeds to a high-resolution settlement mapping of the four mains islands, through image classification and interpretation of remotely sensed aerial images. In the fifth and last research objective, these high-resolution morphological settlement areas are used to propose a novel typological classification of settlement patterns. This classification allows testing the hypothesis that the importance of topographic variables is statistically significant in the location of the islands' settlements.

Overall, this thesis provides an innovative and original contribution to the spatial decision-support systems addressing land use and land cover data. The selected approach relies on proposing novel geographic representations and modeling methods emphasizing the importance of geographical visualization for spatial planning.

Keywords: land use; land cover; land use/cover change; geovisualization; spatial patterns; Macaronesia.

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I. Research outline

I. Research outline

1.1. Introduction

Spatial modeling and analytical techniques are extensively required to analyze geospatial data in order to facilitate the decision-making process at all levels of spatial planning (Nijkamp & Scholten 1993; Geertman & Ritsema Van Eck 1995; Baskent & Keles 2005). Furthermore, over the years geographical research has contributed with several modeling and analytical techniques that would eventually find their way into spatial decision-support systems (e.g. cellular automata based models; agent based models). However, the traditional cartographic representations (i.e. maps) have remained as the dominant geographic representation, and yet, maps are not always the most appropriate medium to visualize geospatial data in all its spatial, temporal, and qualitative dimensions (Nöllenburg 2007). In fact, the continuous increase of spatial modeling and analytical methods has not been fully coupled by an identical increase in geographic visualization methods. Departing from this problem statement, the present research embodies an effort to present novel methods for quantifying and visualizing geographical information, in order to aid the spatial planning decision-making process when addressing land use/land cover (LULC) patterns. In doing so, several modeling and geographic visualization methods are developed and demonstrated by using the Macaronesian islands of Portugal and Spain as study areas.

Macaronesia[1] is a biogeographical region consisting of several archipelagos in the Atlantic Ocean belonging to three countries: Portugal, Spain, and Cape Verde. This research encompasses three archipelagos: the Azores, Madeira, and the Canary Islands. The Azores and Madeira belong to Portugal, whereas the Canaries belong to Spain. From these three archipelagos, the four most densely populated islands were further selected, for the LULC assessments: São Miguel, Madeira, Tenerife, and Gran Canaria. The Macaronesian region has long been overlooked in comparative LULC research for two reasons. First, compared to other mainland regions more prevalent in academic literature, the small size and population of the islands denote spatial dynamics of lower magnitude, which may diminish interest in their study. Second, there is a chronic shortage of comparable and uniform geospatial data for this region. In fact, research recognizes the “lack of homogenous datasets, modeling, monitoring, and mapping strategies throughout the EU” (Temme & Verburg 2011: 46). Because of limited

[1] The name stems from the classical Greek words makárôn (fortunate/blessed) and nêsoi (island). "Islands of the fortunate", was a designation used by ancient geographers when referring the islands to the west of the Iberian Peninsula. The Canary Islands were known, and there was postulation about others.

available land and geographical isolation, the land change process is magnified in these territories in comparison with mainland regions in the long-run. Moreover, these islands are particularly vulnerable to land change, as they have prominently fragile ecosystems (Fernández-Palacios & Whittaker 2008).

Any landscape is continually changing under the influence of different driving forces. Land change – the most noticeable consequence of landscape change – comes from several factors, both natural and anthropogenic[2]. However, natural change is slow. Thus, in a short temporal scale the anthropogenic footprint is decisive and occurs through a combination of different anthropogenic factors (Pijanowski et al. 2002). Understanding how these factors interrelate and how they influence the occurrence of land change is critical to the extent that anthropogenic land change can lead to a wide range of environmental issues (Steiner & Osterman 1988), while also affecting the local and regional economies (Lambin et al. 2001). In fact, the increased awareness of issues related to environmental sustainability, compounded with intensifying land development, has increased the importance of LULC change assessment (Wickham et al. 2000; Jaimes et al. 2010; Peneva-Reed 2014). In order to address the multidimensional impacts of land change, stakeholders resort to spatial planning.

It is important to note that an important share of the issues associated with spatial planning concerns (directly or indirectly) LULC analysis. Moreover, one of the greatest challenges of spatial planning is ensuring a clear and meaningful depiction of geographical information for all the technical elements in the decision-making chain. Broad ranges of stakeholders (e.g. planners, decision-makers, legislators) need LULC data to make informed decisions in planning sustainable development. Additionally, while providing relevant planning data, LULC analysis has also become an important research field. In fact, LULC analysis has long been a platform for testing various strategies of spatial analysis (Falcucci et al. 2007; Feranec et al. 2007; Schulz et al. 2010), models (Pijanowski et al. 2002; Guan et al. 2005; Verburg 2006), and analytical techniques (Barnsley et al. 1993; Epstein et al. 2002; Ackermann et al. 2003). Since LULC analysis is one of the most dynamic fields in geographical research, there is a plethora of published research on LULC analysis, which at first sight may appear as though there are almost no methodological gaps or areas for improvement. Because of this profusion of approaches on LULC analysis, geographers are currently approaching a turning point in LULC research. There are vastly different methodological approaches capable of many findings. It is time that we start exploring these methodological approaches in order to improve the support to the spatial decision-support systems. However, to do this we need user-friendly methods in order to

[2] Created, caused, or produced by human activity.

present complex LULC modeling and analysis to every element in a spatial planning decision-making chain.

Prior to further introducing this research, it is appropriate to establish some definitions. The terms “land use” and “land cover” are not synonymous. Land cover is defined as “the biophysical state of the earth’s surface and immediate subsurface” (Turner et al. 1995: 20), whereas land use “denotes the human employment of land” (Turner and Meyer 1994: 5). As Turner and Meyer (1994) note: “a single land use may correspond fairly well to a single land cover (…) on the other hand, a single class of cover may support multiple uses.” (Turner & Meyer 1994: 5). To put it another way, this research assumes that human use of land cover is what constitutes land use. This assumption is important for a land change analysis since “land-use change is likely to cause land-cover change, but land cover may change even if the land use remains unaltered” (Turner & Meyer 1994: 5) and, while human activity defines land use, land cover change can proceed with or without a proximal human driver (Brown et al. 2012). It is also important to note that, although LULC change is a key component of the urbanization process (Lambin et al. 2001; Grimm et al. 2008), the present research refrains from addressing the urban dimension or urbanization dynamics, because this requires additional data other than LULC. Thus, this thesis focuses on artificial areas, rather than urban areas, the definition of which implies additional multivariate data (Comber 2008; Rindfuss et al. 2008).

Another differentiation also needs to be established early on to avoid misconceptions. First, any data in this research that is georeferenced is considered to be geospatial data. Second, a differentiation is made between two categories of graphical presentations of geospatial data: 1) *geographic representations,* and *2) cartographic representations*. In this research, every graphical depiction of geospatial data in some spatially explicit form is considered a geographic representation. For this reason, all cartographic representations are also geographic representations *per se*. However, some geographic representations do not use a coordinate system or a mathematical projection to derive a graphical depiction of geospatial data. Consequently, geographic representations can have a much more ambiguous spatial reference, and thereby, are less spatially explicit than cartographic representations. Following this reasoning, on the one hand, schematic profiles and cross-sections illustrating geospatial data along a vertical plane are two common examples of geographic representations. On the other hand, common examples of cartographic representations include choropleth maps and cartograms. Since they do not have to follow a strict spatial reference when depicting the data, geographic representations, such as the ones this research proposes, have the ability to create much more flexible geographic visualizations. This approach allows communicating spatial information in ways that are not possible when using traditional cartographic techniques. Because visual representations of geospatial data are indispensable in the construction of scientific knowledge (DiBiase et al. 1992), there is an ongoing interest in relating the potential synergistic overlaps of cartography and information graphics (Nöllenburg 2007). On this matter, research acknowledges that the search for effective spatial information representations has been an on-going effort that has “changed the landscape of making and using maps considerably" (Kraak 2002: 319).

Overall, this thesis provides an innovative and original contribution to the spatial decision-support systems addressing LULC data. The selected approach relies on proposing novel geographic representations and modeling methods that emphasize the importance of geographical visualization for spatial planning. Moreover, this research conforms to the European landscape convention in order to characterize European contemporary landscapes in a trans-regional and trans-border perspective (Jones 2007). Ultimately, the research findings will contribute to the discussion about the sustainable development of the islands.

1.2. Research aim

The aim of this research is to propose novel methods for quantifying and visualizing geographical information in order to aid the spatial planning decision-making process when addressing LULC patterns. In doing so, and while contributing to the scientific research of territories that have been overlooked in comparative LULC research, this research further incites the sustainable development debate with respect to anthropogenic land change, with five research questions and objectives.

1.3. Research questions

Five questions focus the research on the Macaronesian islands of Portugal and Spain, and serve as the methodological point of departure for five research objectives.

1.3.1. First research question

What are the contemporary land use patterns and trends on the Macaronesian islands of Portugal and Spain?

In recent decades human-induced landscape changes were profound at a global scale (Foley et al. 2005). These changes have also affected the small and isolated Macaronesian islands of Portugal and Spain. Because of the islands' ecological importance (Fernández-Palacios & Whittaker 2008; Sundseth 2009), LULC studies are of particular significance to this region. In fact, despite representing only 0.2 percent of the EU territory, the Macaronesian islands of Portugal and Spain host over 25 percent of EU's most endangered and vulnerable flora (Sundseth 2009). For this reason the first research question sets out to analyze and measure in the main land use categories of artificial, agricultural, and forest/semi-natural on eighteen inhabited islands. This establishes the difference of land use areas in order to deduce land use proportions and rates of change by providing a contemporary characterization and quantification of the overall land use patterns and trends within some of Europe's most important biotas. In doing so it contextualizes the remaining research questions, where spatial modeling approaches and novel, spatially explicit graphical methods are employed to have a more detailed and meaningful description about the anthropogenic spatial patterns across the main islands.

1.3.2. Second research question

What is the contemporary pattern of coastal land use on the main islands?

In this region anthropogenic landscapes are much more significant on the coastal areas. In fact, while studying the islands it was clear that the majority of LULC dynamics were restricted to a coastal strip. This happens not only because the territories are islands, but also because of the prevailing attraction from housing and tourism-related infrastructure to build on coastal areas. For instance, over the last decades the growing tourism activity in Macaronesia, especially in the Madeira and Canaries archipelagos, has caused major changes to coastal areas. With this in mind, the role and significance of coastal areas are well documented in several studies (Roth et al. 1989; Small & Nicholls 2003; Thom et al. 2005). Through land development, the increase in artificial surfaces implies the growth of impervious surfaces (JRC-IES 2011). This has impacts in many fields, for instance, land development causes soil sealing which causes water retention to decrease. This causal chain potentially increases the risk of flooding. A higher land development pressure may also lead to the loss of productive soils and an increase in pollution (JRC-IES 2011). As a result, due to increased susceptibility to LULC change, coastal areas demand specific assessments. This importance is magnified in the case of islands. Taking into account that, in these islands the majority of the anthropogenic activities are located along a small coastal strip, it is of the utmost importance to propose this second research question.

1.3.3. Third research question

What is the contemporary altitudinal pattern of land cover on the main islands?

The Macaronesian islands of Portugal and Spain have recent[3] settlement patterns compared to Europe's mainland, and a far less comprehensive public transport system compared to Europe's old settled regions. Human settlement on the islands is conditioned by the rugged physical geography of the islands, and consequently there is much less sprawl in comparison with other newly settled regions dependent on the automobile. Because of steep slopes, cliffs, and ravines, most of these volcanic islands present major topographic constraints for horizontal expansion. Therefore, artificial surfaces are predominately located across the coastal lowland areas. Another key point is that the peoples of the islands resorted extensively to agricultural terraces in order to maximize available agriculture areas. This technique allowed human occupation to rise much higher than naturally possible, thus shaping the vertical landscape of the islands. It is important to note that in contrast to the first two research questions, this third question focuses on land cover patterns. As previously noted, land cover should be perceived as "the biophysical state of the earth's surface and immediate subsurface" (Turner et al. 1995: 20), whereas land use "denotes the human employment of land" (Turner & Meyer 1994: 5). Therefore, for this research question, it was more relevant to study the altitudinal pattern of land cover rather than land use because altitude plays a much more important role in the biophysical cover of the landscape, whereas the human employment of land is less easily constrained through natural factors such as altitude.

1.3.4. Fourth research question

What is the contemporary pattern of land development pressure on the main islands?

LULC change can be perceived as a geographically complex system represented by intricate interactions between man and nature (Wu & David 2002). LULC change comes from several factors. Namely they are policy, economics, culture, and environment, and other less significant factors (Pijanowski et al. 2002). These factors "interact dynamically to give rise to different sequences and trajectories of change" (Nagendra et al. 2004: 114). These combined factors result in LULC driving forces from which LULC change is the visible impact on the landscape.

[3] Colonization began in the early fifteenth century.

In this region land development has been the primary cause of LULC change over the last decades. One should note that the anthropogenic process of land development is responsible for several ecosystem disturbances (Jarnagin 2004; Berlanga-Robles and Ruiz-Luna 2011; Cunningham et al. 2015; Abdullahi et al. 2015). In fact, land development is one of the main anthropogenic process shaping environmental sustainability. However, considerable spatial variability exists in the pattern of land development pressure across the main islands. Thus, this research tries to answer the question presented above, and presents a spatially explicit representation of the patterns of land development pressure on the main islands. This allows determining which islands have been more subjected to land development pressure, and which locations were prone to land development pressure.

1.3.5. Fifth research question

How strong is the relationship between settlement patterns and the terrain on the main islands?

Research acknowledges the need to examine the causal relationships between drivers of LULC change and contextual factors (Entwisle & Stern 2005). Analyzing the role of the terrain in these rugged volcanic islands might help to identify the external influences and interactions involving socio-economic and physical driving forces shaping land change. Assuming that physical conditions remain unchanged over the time-span of a land change analysis, a researcher might be able to distinguish between the driving forces of land change if they know beforehand the measure to which the terrain conditions the settlements. Consequently, to answer this last research question, this research tests if it is possible to quantify the influence of the terrain on the islands' settlement pattern. In doing so, this research models the relationship between a proposed morphological settlement typology and a set of topographical variables, testing the hypothesis that the importance of topographic variables is statistically significant in the location of the islands' settlements.

1.4. Research objectives

Within the field of LULC assessment, a large and growing body of literature has investigated a plethora of landscapes worldwide (Roth et al. 1989; Mas 1999; Yuan et al. 2005; Yagoub & Kolan 2006; Falcucci et al. 2007; Xu et al. 2007; Feranec et al. 2007; Schulz et al. 2010). Consequently, there is a large volume of published studies describing LULC assessment. However, a crucial feature of every study addressing LULC is data presentation. Moreover, although studies examining LULC patterns and trends are diverse and complete (Mas 1999; Yuan et al. 2005; Munsi et al. 2010; Schulz et al. 2010), there is still an area that can be greatly improved: the representation and visualization methods of LULC data.

Throughout this research, the Macaronesian islands of Portugal and Spain serve as the study areas. However, the five research questions give rise to the need to develop novel approaches for LULC assessments. These novel approaches are represented in the research objectives, which stem from the research questions. Moreover, it is import to note that the proposed methods are devised to be applied elsewhere. Research objectives hereafter provide novel techniques in evaluating and managing the landscape of the study areas, while taking into account that they could be applied in other research.

1.4.1. First research objective

Propose a novel method for representing and analyzing LULC patterns and trends.

LULC data is some of the most important geospatial information needed to support spatial planning. Moreover, as researchers have an increasing amount of LULC data, there is a continuous need for tools and methods that synthesize information related to LULC. Besides tabular form, LULC data may also be presented in some graphical form, such as maps and charts. Nonetheless, sometimes the analysis and interpretation of LULC requires specific data representations. Regarding these, research acknowledges that GIS techniques combined with the use of graphs greatly accelerate the process of visual data exploration (Gugl 2009). Because the first research question required analyzing and measuring the main land use categories and their trajectories, this first research objective sets out to develop a novel method for visualizing LULC proportions and rates of change suitable for application to any region requiring an LULC assessment.

1.4.2. Second research objective

Propose a novel method for representing and analyzing coastal patterns.

In Europe coastal management is a key topic in spatial planning. The European Commission operated a program on Integrated Coastal Zone Management (ICZM) in the mid-1990s. After the program ended an “Integrated Coastal Zone Management: A Strategy for Europe” was published. This document gives policy guidelines that progressively promote ICZM in Europe. Overall, ICZM attempts to “balance the needs of development with protection of the very resources that sustain coastal economies” (EEA 2006: 7). Because coastal areas are especially vulnerable to land change (Yagoub & Kolan 2006), there is a need to evaluate land change in order to develop efficient coastal management strategies (JRC-IES 2011). As mentioned, anthropogenic LULC dynamics are more significant on coastal areas because of the attraction from housing and infrastructure developers towards the shoreline. Because the study areas are islands where a small coastal strip has the majority of the LULC dynamics, it was pertinent to propose this second research objective. Therefore, this second research objective sets out to develop a novel method for visualizing coastal patterns suitable for application in other coastal areas requiring a LULC assessment.

1.4.3. Third research objective

Propose a novel method for representing and analyzing altitudinal patterns.

Distance to the coastline is not the only impeding physical factor acting as driving a force of land change. In rugged territories like most[4] of these islands, altitude and slope also constrain much of the horizontal expansion of the artificial surfaces. For this reason in some studies there is a need of simultaneously representing multivariate data for a LULC assessment. However, cartographic representations (e.g. maps), albeit being the most spatially explicit method of representing geospatial data, have the drawback of (in order to maintain legibility) having to constrain data representation to a very small number of variables. Compound glyph-based techniques can be placed on a map display to represent the values of multidimensional attributes (Nöllenburg 2007). However, “if the number of symbols or attributes exceeds a certain limit the symbols become hard to compare” (Nöllenburg 2007: 263). Under these circumstances a visual correlation between several variables of geospatial data requires other geographic representations. This is especially helpful in exploring higher dimensional data sets

[4] The geologically older and eroded islands (e.g. Porto Santo, Fuerteventura, and Lanzarote) are less rugged.

(Dransch 2000). In order to address the third research question: "What is the contemporary altitudinal pattern of land cover on the main islands?", this research would have to offer an insight into the islands' vertical landscape structure. The employed method would have to make clear the altitudinal correlations and processes. Therefore, this third research objective sets out to develop a novel method for visualizing the altitudinal zonation of geospatial data, suitable for application to other mountainous regions.

1.4.4. Fourth research objective

Propose a novel method for deducing and representing land development pressure.

Through the proliferation of infrastructure and buildings, anthropogenic land change causes irreversible alterations of the landscape (Foley et al. 2005). As mentioned, land development is one of the major anthropogenic processes shaping environmental sustainability. Either directly or indirectly, land development pressure influences biophysical environments, biodiversity, and other resources. Research acknowledges that there has been an increasing interest in monitoring and quantifying spatial processes and their driving forces (Herold et al. 2003). However, no standard method exists for evaluating land development pressure. A coherent policy framework that ensures sustainable development needs diagnosis inducing solutions for the problems affecting anthropogenic land change. Because of this, the fourth research objective sets out to develop a novel method for quantifying and analyzing land development pressure, once again, as a method suitable of being applied elsewhere.

1.4.5. Fifth research objective

Propose a novel morphological typology for settlement patterns.

A settlement typology can be defined as the study and interpretation of settlement types and their processes that analyses and interprets the various characteristics of settlements to provide classifications. The typology becomes a toolkit that informs further study and interpretation of settlements and their characteristics, including setting up and selecting categories to organize and analyze new data (Newman et al. 2008). Therefore, prior to answering the fifth research question: "How strong is the relationship between settlement patterns and the terrain on the main islands?" this last research objective proposes a novel settlement typology. Rather than addressing urban areas, the choice of studying settlements makes the process more objective because identifying an urban area involves functional criteria

(Comber 2008; Rindfuss et al. 2008), and this fifth objective only addresses the artificial areas representing the settlements.

The only comparable LULC data available for the Macaronesian islands of Portugal and Spain are the CORINE Land Cover (CLC) datasets. However, CLC have a limited scale for more detailed studies. Since no compatible high-resolution LULC dataset for the study areas exists, in the fifth and last research objective, this research extracts continuous artificial surfaces from high-resolution aerial images. These continuous surfaces are intended to represent settlements and are labeled “morphological settlement areas” (MSAs). According to Herold et al. (2005), the morphological dimension is crucial when assessing spatial patterns, namely through the analysis of the spatiotemporal dynamics of settlements. Based on a categorical, patch-based representation of a landscape, patches or landscape units can be defined as homogenous spatial areas within a specific landscape property of interest, within the context of the spatial phenomenon under consideration (Herold et al. 2005). This patch-based representation of a landscape can be applied in any given area in order to represent discrete areas of artificial land cover.

Settlement differentiation with high-resolution mapping is only possible through a morphological approach. Thus, this research proposes a settlement typology using an exclusively morphological criterion. The morphological criterion for the delimitation of settlements integrates particularly well with remote sensing methods. One of the most significant discussions in this field of study is the approach combining remote sensing and modeling for an improved understanding and representation of spatial patterns (Herold et al. 2003). Therefore, after proceeding to a high-resolution delimitation of settlements in the four main Macaronesian islands of Portugal and Spain, this fifth research objective sets out to propose a novel morphological settlement typology suitable for application in other regions.

1.5. Geospatial data

This section provides a short overview of the data that is used in the research. The primary data sources are the CLC datasets. CLC are a map of the European landscape based on remote sensing. These public domain datasets[5] provide an inventory of land cover classes organized hierarchically in three levels as a comparable cartographic product (25 ha minimum mapping unit). CLC are available at 100 m resolution grids and provide an inventory for the years of 1990, 2000, and 2006.

CLC level 1 corresponds to the main categories (i.e. artificial surfaces, agricultural areas, forests and semi-natural areas, wetlands, water bodies), CLC level 2 covers land cover entities at a higher level of detail (15 classes), and finally CLC level 3 is composed of 44 land cover classes (Table 1). Therefore, the aggregated CLC level 1 characterizes land use, while CLC level 2 onward characterizes land cover. This research uses CLC level 1 and CLC level 2. Which level is used depends on the research question. Table 1 hierarchically organizes the CLC nomenclature according to the three levels: CLC level 1 (land use) and CLC level 2 and CLC level 3 (land cover).

LULC change can be studied by selecting it from the CLC areas that changed over the years. The areas that experienced change are available for 1990-2000 and 2000-2006.The acquired layers "CLC 1990-2000 changes" and "CLC 2000-2006 changes" represent only those areas that experienced change over the years.

To represent topographic related variables in the study areas, a digital terrain model from the "ASTER Global Digital Elevation Model version 2" (GDEM2) with a grid spacing of 30 m was acquired . GDEM2 is a joint product developed by Japan and the United States. The topographic variables altitude, aspect, and slope were deduced from GDEM2. Altitude was expressed in meters above sea level. Aspect in positive degrees from 0° to 360° was measured clockwise from the North. Finally, slope was expressed in degrees.

[5] http://www.eea.europa.eu/data-and-maps

Table 1. CORINE land cover nomenclature.

LAND USE	LAND COVER	
CLC level1	CLC level2	CLC level3
Artificial surfaces	Urban fabric	Continuous urban fabric
		Discontinuous urban fabric
	Industrial, commercial and transport units	Industrial or commercial units
		Road and rail networks and associated land
		Port areas
		Airports
	Mine, dump and construction sites	Mineral extraction sites
		Dump sites
		Construction sites
	Artificial, non-agricultural vegetated areas	Green urban areas
		Sport and leisure facilities
Agricultural areas	Arable land	Non-irrigated arable land
		Permanently irrigated land
		Rice fields
	Permanent crops	Vineyards
		Fruit trees and berry plantations
		Olive groves
	Pastures	Pastures
	Heterogeneous agricultural areas	Annual crops associated with permanent crops
		Complex cultivation patterns
		Land principally occupied by agriculture, with significant areas of natural vegetation
		Agro-forestry areas
Forests and semi-natural areas	Forests	Broad-leaved forest
		Coniferous forest
		Mixed forest
	Scrub and/or herbaceous vegetation associations	Natural grasslands
		Moors and heathland
		Sclerophyllous vegetation
		Transitional woodland-shrub
	Open spaces with little or no vegetation	Beaches, dunes, sands
		Bare rocks
		Sparsely vegetated areas
		Burnt areas
		Glaciers and perpetual snow
Wetlands	Inland wetlands	Inland marshes
		Peat bogs
	Maritime wetlands	Salt marshes
		Salines
		Intertidal flats
Water bodies	Inland waters	Water courses
		Water bodies
	Marine waters	Coastal lagoons
		Estuaries
		Sea and ocean

Source: European environmental agency (http://www.eea.europa.eu/data-and-maps).

As mentioned, CLC is the only uniform LULC database covering the Macaronesian islands of Portugal and Spain. However, a major issue is that, for many applications, CLC's resolution is too coarse. Nonetheless, remote-sensed imagery is another prevailing data source for the islands. Remote sensing of artificial environments is particularly challenging since the land surface objects have a small spatial extent. Given this large amount of spatial heterogeneity, most high-resolution mapping has relied upon aerial photography as a data source (Herold & Roberts 2010). Because of the complexity and heterogeneous nature of artificial surfaces, several studies have demonstrated that high spatial resolution imageries are required in artificial environment analysis (Jensen & Cowen 1999; Herold et al. 2002; Blaschke et al. 2004). Because of this, 0.5 m resolution orthophotos[6] were acquired from the "Instituto Geográfico Português" and "Cartográfica de Canarias," the public companies responsible for geographic information production on these islands. The acquisition dates are as follows: São Miguel, 2006; Madeira, 2006; Tenerife, 2008; Gran Canaria, 2008.

This research used a generalization of the acquired orthophotos at a 5 m pixel resolution, accomplished using a nearest neighbor resample. Afterwards, the images were mosaicked to obtain a single file for each island. Because this research was intended to focus on large geographical areas (i.e. four islands), a 5 m spatial resolution was selected. A viable resolution to accommodate the data processing had to be used, and furthermore, there is literature consensus that a 5 m resolution is sufficient for the identification of built-up areas (Jensen & Cowen 1999).

[6] Aerial images geometrically corrected for topographic relief, lens distortion, and camera tilt.

1.6. Thesis structure

There was the choice of either writing this thesis as a traditional monograph or presenting it as a series of articles. Since the articles format was chosen, the methodological approaches to the research objectives have been published in peer-reviewed journals. This thesis provides the space for the presentation of the results, which was not possible to do in the articles. For instance, the *Journal of Maps* requires a maximum of 4000 words per article, and the analysis is limited to the techniques used in the methods. Therefore, the journal requires that the presentation of the findings be addressed elsewhere. Moreover, the thesis chapters also helped to make the research connections explicit as it tied the individual articles together in terms of theory, spatial domain, and methods. An effort was made to summarize all key theoretical and methodological elements of this research in the chapters of the thesis. Therefore, the thesis should be able to stand independently in case the reader skips the articles. However, for an in-depth description of the applied methods, the reader is better off referencing the published articles. The methodological approaches are best explained in the published articles, whereas this thesis focuses on presenting the study areas, setting up the theoretical framework of the research, and presenting the results more thoroughly than in the published articles.

Table 2 illustrates the organization of the thesis. After a first chapter that introduces the research and formulates the aim, questions, and objectives, the second chapter presents the theoretical framework of the research. This second chapter should not be seen as a “literature review” because each published article addresses the relevant literature concerning each research objective. Instead, this theoretical framework provides scientific justification for this research. On the one hand, the first three sections of the second chapter relate to cartographic communication, integration of cartography with information graphics, and geographic visualization. These are the focus of the first three articles. On the other hand, the fourth and final section of the second chapter addresses GIS-based modeling of LULC data. These are the focus of the last two articles.

The third chapter presents the study area, the Macaronesian islands of Portugal and Spain. The chapter begins by succinctly presenting the archipelagos and the four most densely populated islands: São Miguel, Madeira, Gran Canaria, and Tenerife. This research considers these four islands as the main Macaronesian islands of Portugal and Spain. The second section of this third chapter addresses relevant LULC studies about the islands. Afterwards, the third section of this chapter summarizes the driving forces behind land use in the Macaronesian islands of Portugal and Spain in order to frame a discussion about the processes and dynamics shaping LULC in the region.

Table 2. The thesis structure.

I. Research outline	1.1. Introduction	
	1.2. Research aim	
	1.3. Research questions	1.3.1. First research question
		1.3.2. Second research question
		1.3.3. Third research question
		1.3.4. Fourth research question
		1.3.5. Fifth research question
	1.4. Research objectives	1.4.1. First research objective
		1.4.2. Second research objective
		1.4.3. Third research objective
		1.4.4. Fourth research objective
		1.4.5. Fifth research objective
	1.5. Geospatial data	
	1.6. Thesis structure	
II. Theoretical framework	2.1. Cartographic communication	
	2.2. Integration of cartography and information graphics	
	2.3. Geographic visualization	
	2.4. GIS-based modeling of LULC data	
III. The Macaronesian islands of Portugal and Spain	3.1. Spatial domain	
	3.2. LULC studies about the Macaronesian islands of Portugal and Spain	
	3.3. The driving forces of land use on the Macaronesian islands of Portugal and Spain	3.3.1. Farming-related pressure
		3.3.2. Arson forest fires
		3.3.3. Demographic pressure
		3.3.4. Real estate and tourism-related pressure
IV. Peer-reviewed articles	4.1. Background information	
	4.2. #1 Article	
	4.3. #2 Article	
	4.4. #3 Article	
	4.5. #4 Article	
	4.6. #5 Article	
V. Conclusions	5.1. Conclusions with regard to the research aim	
	5.2. Conclusions with regard to the research questions	5.2.1. First research question
		5.2.2. Second research question
		5.2.3. Third research question
		5.2.4. Fourth research question
		5.2.5. Fifth research question
	5.3. Future lines of research.	
Appendix		

The fourth chapter is dedicated to the published peer-reviewed articles. The chapter begins by providing some background information for the articles. Afterwards, each article is introduced and presented.

The fifth chapter concludes the thesis bringing the main findings with regard to the research questions and objectives together. It is important to note that, due to the *Journal of Maps* exigencies[7], the fifth chapter has detailed information on the findings of the first three research questions. Because the presentation of the findings could not been presented in the first three articles, the key findings had to be addressed elsewhere. Therefore, a choice was

[7] A typical article will not exceed 2000-4000 words, describing the data presented in the map and any pertinent techniques used during the mapping process.

made to present the key findings with regard to the first three research questions in the fifth chapter. The fifth chapter ends by addressing some future lines of research.

Lastly, the thesis ends with the presentation of several figures in an Appendix. This approach was necessary because some of the published maps have a very large format (e.g. ISO-A0), and are to be viewed in their original PDF digital format as a supplement to the articles. Therefore, they are illegible in the printed ISO-A4 paper size format of the thesis. To overcome this issue, the same data views that make up the published maps are presented in the final Appendix as a series of figures.

II. Theoretical framework

II. Theoretical framework

2.1. Cartographic communication

The problem statement of this research is the continuous increase of spatial modeling and analytical techniques has not been fully coupled with a coinciding increase of geographic visualization methods. Consequently, this research aims to propose novel methods for quantifying and visualizing geographical information. As the concept of communicating the spatial dimension plays a major role in this research, the concept is essential to define within cartographic communication.

Human communication is an intricate process using words, sounds, signs, and other forms of expression. Essentially communication is the act of transferring information in which participants engage in an exchange of information through an encode/decode process. In response to such needs, cartographic representations are essential for communicating information that has a spatial dimension. With this in mind, cartographic representations, such as maps, can be regarded as the most complex form of visual communication (DiBiase 1990). Through spatial abstraction and data encoding, cartography provides powerful means to depict and communicate information that has a spatial dimension (Fairbairn, 2015). Furthermore, its effectiveness explains why cartography has been an integral part of human history (Harley & Woodward, 1987).

Over centuries of human history, the prevailing cartographic representations - maps - have been used in two ways: (1) as a medium of recording and storing geographical information (2) and as a method of communicating encoded geographical information (Jiang 1996). However, up until the mid-twentieth century there was no body of work integrating cartography scientifically. For this reason, in the 1950s Arthur Robinson introduced the systematic principles for an effective cartographic communication, and developed several design principles trying to improve the communication of geographical information. In their most basic form, the principles behind Robinson's cartographic communication entail the selection and symbolization of geographical information and the process of recognition by the user(s). In his seminal works, Robinson (1952, 1953) noted that cartographic communication is composed of three stages: (1) *source* (i.e. the graphical encoding of geospatial data), (2) *channel* (i.e. the cartographic representation), and (3) *receiver* (i.e. the user(s) decoding the geospatial data).

Any geographic representation is made of some sort of graphical encoding of geospatial data. The creation of a common ground for the decoding of the depicted data is usually attained trough a legend explaining the graphical encoding of geospatial data. Following a successful encoding the user(s) can decode the encoded geographic information. The scientific principles behind the graphical encoding of geospatial data were settled in the 1960s, when Bertin ([1967] 2010) devised a systematic approach to cartographic symbolization, and provided a conceptual framework for cartographic communication through the science of semiotics.

Robinson's (1952, 1953) cartographic communication, and Bertin's ([1967] 2010) systematic approach to cartographic symbolization helped articulate cartography in scientific terms with the ultimate goal of effectively communicating geographical information. As a result, up until the late 1980s, Robinson's cartographic communication was the predominant paradigm in cartography. The map functioned as not only a hardcopy database of geographical data but also as an information transfer medium, the same role it had had over centuries. However, as digital technology proliferated, cartography also started to switch from an analog to a digital framework. In the 1980s the mass production and widespread use of computers would dictate the conversion from analog (i.e. hardcopy) to digital mediums. As digital became the standard, the reasoning approaches to cartographic representations were also changing.

One should note that in the past geographic representations had not been restricted to cartographic representations, as can be seen in the work of Alexander von Humboldt in the early nineteenth century (Buttimer 2012). However, contemporarily digital graphics open new possibilities for further innovations. Consequently, geographic representations needed to be understood in a different way than was possible in the analog-oriented cartographic communication models. In the 1990s the expansion of the internet brought sweeping changes, and the 2000s saw dedicated online mapping services such as *Google Maps*[8], thereby introducing cartography to mass culture. In the realm of cartography this was a significant change because, as some authors noted, "in the past, the time between production and use could be years, today it can be seconds." (Kraak 2002: 319). Moreover, on-line digital cartographic representations started to provide a direct interface for geospatial data. After centuries of human history, maps were no longer a hardcopy medium of registering and communicating geographic information. This is why Kraak (1999: 157) noted that, with the turn of the millennium "maps are now an integral part of the process of spatial data handling."

In the 1990s, with the widespread adoption of digital cartography, a distinction started to be made between geospatial data and the presentation functions of cartographic representations. This distinction became known as the *digital landscape model* and *digital cartographic model* (Brassel & Weibel 1988; Hesse & Williamson 1993; Hurni & Leuzinger 1995). This distinction designates a *digital landscape model* as a model of geographical reality, encoded in a digital database through a data structure and a *digital cartographic model* as a cartographic

[8] Google Maps was launched in February 2005.

representation of the *digital landscape model*. The present research builds upon this framework by introducing the definition of *digital geographic model*. As mentioned in the introduction section, in this research a differentiation is made between *geographic representations* and *cartographic representations*. Contrary to cartographic representations, geographic representations can have a much more ambiguous spatial reference, because they do not have to use a coordinate system, nor a mathematical projection to derive the depiction of geospatial data in order to maintain the spatially explicit accuracy of cartographic representations. As multiple *digital cartographic models* can be generated from the same *digital landscape model*, many possible *digital geographic models* can likewise be constructed from the same *digital landscape model*. For instance, this research extensively uses the same *digital landscape model* – the CORINE Land Cover datasets – in constructing several distinct *digital geographic models* from this dataset.

2.2. Integration of cartography with information graphics

Cartographic representations are often integrated with text and information graphics that help users more easily assimilate the depicted information. One of the main reasons for coupling different methods of representing geospatial data is that they can provide complementary insights for the data. Generally speaking, cartographic representations are the most effective means of communicating geographical information. However, cartographic representations are but one way of presenting and disseminating geospatial data, and they are not always the most appropriate mode to visualize geospatial data in its spatial, temporal, and qualitative dimensions (Nöllenburg 2007). In addition, research acknowledges that conventional maps are inconvenient to be used as analytical tools (Jiang 1996). The reason for this is the potential value of spatial abstractions, assimilating and relating spatial correlations and patterns, may not be appreciated fully in a traditional map. Thus, "the ability to envision data in a variety of forms is a necessity" (DiBiase et al. 1992: 201).

As mentioned, geographic representations can assume multiple formats and different spatially explicit approaches other than the traditional cartographic representations (i.e. maps). Moreover, due to the continuous increase of geospatial data, research faces a growing demand for tools and methods for synthesizing spatial information (Nöllenburg 2007). GIS techniques combined with visualization greatly accelerate the process of visual geospatial exploration (Gugl 2009). However, geospatial data can be of different dimensionalities or stored in various types of digital landscape models that need to be related or combined in the visualization. This heterogeneity of the geospatial data characteristics, coupled with the need to convey both the attribute and geographic space, enhances the technical challenges in designing meaningful geographic visualization techniques.

Typically the graphical depiction of geospatial data is done by resorting to single maps "to focus on only one aspect of a spatial pattern, for which only one map is necessary" (Jiang 1996: 8). Yet, it is also possible to use pairs of single-variable maps or a single multivariable maps to analyze geographical correlations among spatial phenomena (Battersby et al. 2011). Although this may be possible, the most powerful means of analyzing attribute space is through information graphics, such as charts. This is why research acknowledges that, "graphs and diagrams should be used to present information on quantitative and qualitative relationships" (Dransch 2000: 7). Then again, information graphics cannot convey geographical space appropriately. For this reason, the study of spatial patterns can be greatly leveraged through the integration of cartography and information graphics. This offers a more flexible approach in order to visualize spatial information from different spatially explicit approaches based on the same digital landscape model.

The use of computerized techniques in geographical research, in conjunction with the theoretical foundations of visualization put forth by Bertin ([1967] 2010) and Tufte's ([1983] 2001) framework of information design, opened new possibilities for accurate static representations of geospatial data. The fields of visualization and information design provide methods to present all the information in a data structure in one single static image. These methods typically encompass the presentation of information in primarily graphical or pictorial form. Thus, the same theoretical background and best practices of visualization and information design methods (Bertin, [1967] 2010; Tufte [1983] 2001; Cleveland 1993) can also be applied to geographic representations. However, the graphical representation of geospatial data necessitates specific methods that maintain a meaningful and spatially explicit representation. A critical issue with graphical representations of geospatial data resides in the need to display "both the attribute space familiar to the statistician and the geographic space that provides the necessary sense of place and relative location" (Monmonier 1990: 38). Moreover, "a graphical method is successful only if the decoding is effective" (Cleveland & McGill 1985: 828).

A major drawback with extant cartographic methods arises from legibility issues when displaying high-dimensional geospatial data in a single-data view (Nöllenburg 2007). Standard or geometrically transformed static information graphics, such as graphs, charts, and parallel coordinate plots are an alternative. Nonetheless, in the case of a research with a large geographical extent, the entire study area cannot be accommodated all at once in the display area of a single-data view. This issue arises due to the multiple compass directions required to represent the data. Moreover, whenever it is convenient to present the results in a spatially explicit display, this approach cannot conveniently be accomplished by resorting to other extant methods, such as tables. On the one hand, traditional cartographic approaches are the most spatially explicit methods for representing geospatial data in a single static 2D data view. However, they have limitations when representing multivariate data, as they are prone to visual effectiveness issues. On the other hand, attribute space is best represented in a tabular format. Tables reveal all data values explicitly, a task that is difficult to do with a traditional cartographic approach. However, tables are not spatially explicit; therefore, they cannot visually convey geographic space. It is important to realize that, when dealing with large data sets, the only convenient way to display the data in a compact tabular format implies dimensionality reduction techniques to derive latent variables describing a proportion of the data's inherent information. By doing so standard or geometrically transformed static displays, such as graphs, charts and parallel coordinate plots are straightforward methods for displaying the attribute space of geospatial data, although they are not spatially explicit. Charts can even add some spatial context when relating entities to each other namely through position. However, these methods have difficulties in conveying both the attribute and geographic space of high-dimensional geospatial data. Therefore, the need arises for custom-made information graphics such as the ones proposed in this research to overcome the main drawbacks of extant methods. Consequently, the first three research objectives of this research try to increase the level of integration between cartography and information graphics by transposing some of the spatially explicit accuracy of the cartographic representations into custom-made information graphics and thus, creating novel geographic visualization methods.

2.3. Geographic visualization

In the 1980s the widespread adoption of graphical user interfaces on most kinds of computer devices allowed scientific visualization to become increasingly important in all fields of research. In fact, MacEachren and Kraak (1997) remark that the work of McCormick et al. (1987) on visualization in scientific computing was pivotal research contributing to visual representations in science. Gradually the advancements in computer processing power would allow immersive and interactive virtual environments that could be used to explore and present geospatial data (Kraak 2002). MacEachren and Kraak (1997: 336) define scientific visualization as "the use of sophisticated computing technology to create visual displays, the goal of which is to facilitate thinking and problem solving." In doing so, scientific visualization provides "powerful tools to set up and present analysis procedures and to present the information itself" (Jiang 1996: 3).

As mentioned, communication and visualization are intrinsic to the process of exchanging geographical information and the digital revolution changed cartography. However, up until the 1990s, a coherent theory for information visualization in cartography was still lacking. Progress in semiotics (Bertin [1967] 2010), visual data mining (Tukey 1977), and scientific visualization (McCormick et al. 1987), motivated DiBiase (1990) to propose a functional model for cartographic visualization. The model was intended to “encourage cartographers to direct attention to the role of maps at the early stages of scientific research where maps and map-based tools are used to facilitate data sifting and exploration of extremely large data sets" (MacEachren & Kraak, 1997: 336).

In DiBiase’s model cartographic visualization is used to support geographical research. The model consists of two activities, *visual thinking* and *visual communication*. Visual thinking is exploratory, whereas visual communication is explanatory (DiBiase et al. 1992). To elaborate, visual thinking is a cognitive process that determines data significance, produces insights on patterns, and finds relationships among geospatial data in order to generate questions and hypotheses about the problem under investigation (Dransch 2000). Visual communication takes place when the results of visual thinking are represented into a way others can see and understand with minimal effort. Visual communication has to present information “in such a way that a person can create step-by-step knowledge about the subject” (Dransch 2000: 8). As DiBiase (1990) noted, on a more detailed level, cartographic visualization has different functions at different stages of scientific research. The author identifies a four-stage process: (1) *exploration of data*, (2) *confirmation of hypotheses*, (3) *synthesis of hypotheses*, and (4) *presentation of results*. The first two stages represent visual thinking whereas *synthesis* and *presentation* relate to visual communication. DiBiase’s approach remains the dominant knowledge-based map-use paradigm and is an example of higher-order analytical cartographic tasks used to support geographical research. The present research follows this functional model but strengthens the importance of visualization, not only for scientific research purposes, but also to support the spatial decision-support systems addressing LULC data, and more broadly, the decision-making process at all levels of spatial planning.

As established by DiBiase (1990), cartographic visualization can provide an insight into an investigated phenomenon, verify a derived hypothesis, and communicate the results (Dransch 2000). Moreover, the widespread adoption of computers, coupled with rapid advances in computer graphics technology, allowed MacEachren and other authors (MacEachren et al. 1992; DiBiase et al. 1992; MacEachren 1994) to focus on the first two stages of DiBiase’s (1990) model: *exploration* and *confirmation* (i.e. visual thinking). This new approach expanded DiBiase’s functional model by introducing a new multidisciplinary research field - *geovisualization* – a novel way of conceptualizing the spatial dimension. As an interdisciplinary area, geovisualization integrates visualization approaches from several scientific fields to provide “theory, methods, and tools for visual exploration, analysis, synthesis, and presentation of geospatial data” (MacEachren & Kraak 2001: 3). MacEachren et al. (1992) defined geovisualization as "the use of concrete visual representations - whether on paper or through computer displays or other media - to make spatial contexts and problems visible, so as to engage the most powerful human information-processing abilities, those associated with vision." This novel approach was a leap forward in conceptualizing geographical space. Since then, geospatial data started being visualized in a number of alternative ways using multiple representations without constraints set by traditional techniques or rules (Kraak 2002).

Geovisualization methods range from static 2D to dynamic 3D applications, and in contrast to information visualization displaying any abstract data, “geovisualization deals specifically with geospatial data” (Nöllenburg 2007: 264). Static presentations (Battersby et al. 2011) are constructed from visual variables within 2D or 3D spatial dimensions, but static presentations are essentially atemporal (DiBiase et al. 1992). On the other hand, dynamic presentations (Andrienko et al. 2008) add a fourth visual dimension – time – to represent dynamic processes through dynamic data displays. For instance, a key feature of geovisualization is the capability to uncover hidden spatio-temporal patterns (Slocum et al. 2001). This capability made possible visual data mining, a “human-centered task that aims at visually analyzing data and gaining new insights” (Nöllenburg 2007: 268).

In a wider sense, a geovisualization approach emphasizes visual data exploration over data presentation (Crampton 2001). Presentation is mainly concerned with depicting information, whereas geovisualization’s focus – *visual exploration* – is related to the discovery of unknown information (Jiang 1996). Thus, in a geovisualization environment “maps are used to stimulate (visual) thinking about geospatial patterns, relationships, and trends” (Kraak 2002: 322). Consequently, "emphasis is not on storing knowledge but on knowledge construction" (MacEachren & Kraak 1997: 336). MacEachren and Ganter’s (1990) cognitive approach to geovisualization focuses on the explorative side of visualization by using images instead of words for gaining new scientific insight. Building upon the cognitive approach to geovisualization, several alternative portrayals of geospatial data have been proposed (Wood et al. 2010; Speckmann & Verbeek 2010; Eppstein et al. 2013; Evans et al. 2013). Research acknowledges there is a growing need for novel approaches to represent geospatial data in a visual form that improves pattern recognition and hypothesis generation (Bodum 2005). In order to improve pattern recognition and hypothesis generation, maps should be seen as an “interface to geospatial data that can support information access and exploratory activities, while it retains its traditional role as a presentation device” (Kraak 2002: 320). Moreover, the increasing use of geospatial data “establishes geovisualization an essential element of 21st century information use, a genuine opportunity for 21st century Cartography and a requirement for modern map users.” (Dykes et al. 2005: 4).

Research acknowledges the broader application of sophisticated visualization tools in geography (Nöllenburg 2007). Therefore, geovisualization has become a significant area for applied research (Dykes et al. 2010). Since its inception, geovisualization was regarded as an important contribution to spatial knowledge discovery. In geographical research, knowledge discovery relies heavily on modeling and spatial analysis. As a result, from early on there was a “trend to combine visualization and spatial analysis thereby allowing them to benefit each other” (Jiang 1996: 3). Although geovisualization is mainly concerned with the visual exploration of geospatial data, some authors regarded geovisualization as an extension of spatial analysis (Jiang 1996). Furthermore, research has demonstrated several examples of the application of spatial modeling approaches coupled with geovisualization techniques (Kwan 2000; Chertov et al. 2005; Mitasova et al. 2006; Nordvik et al. 2009). These same principles can be applied for the coupling of modeling methods integrating visualization and LULC dynamics. The coupling of geovisualization and GIS-based modeling of LULC data generates a powerful tool that conveys change in a landscape. For example, geovisualization allows the representation of time-series and spatial patterns of land change in alternative graphical forms other than the traditional map, thus facilitating the analysis of LULC dynamics.

Research acknowledges visual methods as particularly important to modelers, “for whom visual representations are windows not only to the realities they attempt to simulate, but to the workings of the models themselves” (DiBiase 1990). This can be done with the help of modeling and geovisualization, coupling modeling approaches with spatial visualization of the results. Therefore, geovisualization approaches provide the possibility of carrying out extensive transformations and changes to geographic representations, thus enabling an improved knowledge-building process when using geospatial data. Moreover, “the results of spatial analysis operations can be displayed in well-designed maps easily understood by a wide audience” (Kraak 1999: 158). In this thesis geographic visualization makes it possible to answer several research questions. The novel geovisualization methods presented hereafter allow a novel insight into the islands’ anthropogenic patterns, and highlight the strengths and research possibilities of coupling geovisualization with GIS-based modeling approaches.

2.4. GIS-based modeling of LULC data

The basis of the quantitative revolution in modern geography was the application of the hypothetico-deductive method to geographical research. The logic underlying the hypothetico-deductive method is that a given spatial phenomena can be explained by a scientific theory but should be open to experimentation, and therefore, refutation. From this perspective introduced into geography during the 1950s through the 1960s, the quantitative revolution led to the dissemination of modeling approaches to geographical analysis (Melamid 1955; Lukermann & Porter 1960; Harvey 1966; Tobler 1970). Besides their theoretical framework, these models were validated through the coupling of data and statistical techniques (Thomas 1961; Lund 1963; Wilson 1970; Willmott 1981). Progressively, the study of the spatial distribution of patterns became the cornerstone for quantitative studies in geography (Cliff & Ord 1975; Ripley 1977; Marshall 1991).

GIS-based modeling approaches can be broadly classified into *empirical* and *process* models. Empirical models focus on the relationships between the variables of the model, seeking "to describe the statistical relationships among data with limited regard to an object's internal structure, rules, or behavior" (Korzukhin et al. 1996: 879). Process-based modeling can be defined as a procedure by which the behavior of a system is derived from a set of functional components and their interactions with each other and the system environment, through physical and mechanistic processes occurring over time (Mäkelä et al. 2000). Thus, process models emphasize the interactions between all the components of a system. The simplicity of the mathematical models and the small number of variables employed characterizes empirical models. Consequently, they are efficient for making predictions, although they have limitations in addressing relationships and identifying the causal aspects of the system (Korzukhin et al. 1996). Process models attempt to describe the system as a whole by attempting to represent the interactions of all its components. Through the fourth and fifth research objectives, this thesis addresses two examples of empirical models applied to GIS-based modeling of LULC data. The usefulness of representing spatially distributed GIS-based modeled data is an important research field for the definition of anthropogenic impacts, and for the identification of the driving forces of land change (Leh et al. 2013; Ligmann-Zielinska 2013; Gessesse et al. 2014; Vacquie et al. 2015).

Besides being classified as empirical or process, GIS-based modeling approaches can further be classified as *deterministic* or *stochastical*. The initial configuration of an empirical model is commonly obtained through historical data (e.g. through time-series of data). In this case, when only known inputs are used to represent the model, the model is classified as deterministic because the outcome is known due to the use of only known input. The inverse distance weighted interpolation method used in the fourth objective is deterministic, since the model has no random components. Nonetheless, other geostatistical methods use the stochastical theory of spatial correlation both for interpolation and for apportioning uncertainty (Burrough 2001). When randomness is used to explain the system, the model is classified as *stochastic*, which, besides known inputs, also uses a random component for the modeling of phenomena.

The quantitative revolution approach placed great emphasis on spatial analysis and statistics. Thus, concepts arising from statistics became increasingly important. A crucial concept derived from statistical theory is *spatial stationarity*, a concept that indicates an area in which statistical properties are a function of distance and direction (Tobler 1979). Slowly, a novel approach started to be applied through the application of *geostatistics*, a class of statistics used to analyze and predict the values associated with spatial phenomena (Matheron 1963). Geostatistics provided a means of exploring spatial data and generating continuous surfaces from sampled data points using procedures such as spatial interpolation (Burrough 2001). Initially proposed for the modeling of natural resources (Matheron 1963), geostatistics became increasingly used in other fields and as well as being used for the spatial analysis of LULC data (Karnieli et al. 2008). In the case of this thesis, the fourth research objective is an example of the application of geostatistics for the modeling of LULC data.

Several LULC studies are devoted to the analysis of the relations between LULC and the socio-economic and biophysical variables that act as the driving forces of land change. It is important to note that the distinction between land use and land cover is important when dealing with GIS-based modeling approaches because “it affects both the data requirements for calibration and validation and the process representations required” (Brown et al. 2012). Lesschen et al. (2005) subdivide LULC driving forces into two groups, *proximate causes* and *underlying causes*. According to the authors, proximate causes are the activities and actions that directly affect LULC, whereas underlying causes are the forces that underpin the proximate causes, which include demographic, economic, technological, institutional, and cultural factors (Lesschen et al. 2005).

In order to address sustainability concerns, a plethora of studies have aimed to understand the processes of land change and their main driving forces through GIS-based modeling. Recent examples include the deduction of the probability of LULC change (Mas et al. 2014), the mapping of risk areas (Leh et al. 2013), the prediction of the intensity and/or location of LULC change (Asselen & Verburg 2013), and the analysis of the impacts of LULC changes (Nagendra et al. 2013).

Regarding GIS-based modeling of LULC data, it is important to note that, the impacts arising from anthropogenic land change are not always negative. From social and economic standpoints, a significant land change dynamic is always inevitable in a modern society. Despite having an environmental impact, anthropogenic land change is both inevitable and necessary for any given society. Therefore, an important issue arises in the sustainability of land change and the appropriate balance between the social, economic, and environmental dimensions. The last decades marked the emergence of studies in several research fields devoted to the paradigm of sustainable development, the definition of which is derived from the Brundtland commission[9].

At the turn of the millennium, there had been an increasing amount of literature on settlement typologies and urban forms because researchers have sought to understand settlements within a sustainability context (Du Plessis, 2002). Due to the potentialities provided by GIS approaches, several studies addressed the spatial dimension and its relation with sustainable land development. In this field of research, a significant discussion addressed the analysis of sprawl.[10] For instance, Torrens & Alberti (2000) developed an empirical landscape approach to sprawl measurement that focuses on the characteristics of density, scatter, the built environment, and accessibility. Alberti & Waddell (2000) investigated a specific set of spatial metrics for LULC models that incorporate human and ecological processes. Wassmer (2000) proposed methods and measures to quantify and compare sprawl in metropolitan areas. Moreover, several authors (Galster et al. 2001; Hasse & Lathrop 2003; Song & Knaap 2004) adopted a multidimensional approach for analyzing urbanization spatial patterns through composite indicators by linking specific LULC patterns with socioeconomic characteristics. These approaches have been especially useful in a rigorous effort to integrate a plethora of socioeconomic, demographic, and morphological variables. However, methods that solely employ a morphological dimension are also needed to further evaluate spatial dynamics (Herold et al. 2005). Hence the pertinence of the fifth research objective, which proposes a novel morphological typology for settlement patterns.

Following the broader classification of modeling approaches into empirical and process models, Brown et al. (2012) classify GIS-based modeling approaches of LULC data using two categories: *empirically fitted* and *dynamic process models*. LULC empirically fitted models are based on statistically matching temporal trends and/or spatial patterns (i.e. the dependent variable) with some set of predictor variables acting as LULC drivers (i.e. the independent variables). According to Brown et al. (2012), one of the most common approaches to a LULC empirically fitted model is “to estimate a logistic regression function that describes either the

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[9] In the 1980s the UN established this commission to incentivize nations to pursue sustainable development. The outcome was the “Brundtland report,” a 1987 document that defined the meaning and goals of “sustainable development."

[10] Sprawl is unplanned and uneven pattern of land development, driven by a multitude of processes, and leading to inefficient resource utilization (Bhatta et al. 2010).

probability of a particular land category occurring or of the location transitioning from one land category to another." In this thesis the fifth research objective resorts to an empirically fitted model supported by a multinomial logistic regression that analyzes the relationship between a proposed typology of settlement patterns (i.e. the dependent variable) and a set of topographical variables (i.e. the independent variables). Multinomial logistic regression is used for cases where dependent variables have more than two categories, such as the proposed settlement typology. According to Lesschen et al. (2005), multinomial logistic regression estimates the direction and intensity of the explanatory variables on the categorically dependent variable by predicting a probability outcome associated with each category of the dependent variable.

The remaining category of GIS-based modeling approaches of LULC data are the dynamic process models. These are the most ambitious GIS-based models of LULC data. These models seek to simulate the most important interactions between the components of a LULC system, hence their complexity. Broadly speaking, LULC dynamic process models deemphasize the fitting of data and emphasize the fidelity of model elements and processes to give novel insights about the processes (Brown et al. 2012). The most common application of LULC dynamic process models are *cellular automata* (Al-shalabi et al. 2013; Jiang et al. 2015), and *agent-based models* (Filatova 2015; Magliocca et al. 2015). LULC dynamic process models are not addressed in this thesis.

In sum, within the quantitative approach, geographic research adopted the computer as the fundamental analytical tool. The emergence of the quantitative approach coupled with the dissemination of computers gave great impetus to GIS-based modeling. Nowadays, GIS-based modeling is widely regarded as a fundamental tool for geographical research and is furthermore applied to the LULC data in the last two research objectives of this thesis.

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III. The Macaronesian islands of Portugal and Spain

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3.1. Spatial domain

Macaronesia is a biogeographical region consisting of several archipelagos in the Atlantic Ocean belonging to three countries: Portugal, Spain, and Cape Verde. This research encompasses three archipelagos: the Azores, Madeira, and the Canary Islands. The Azores and Madeira belong to Portugal, and the Canaries belong to Spain. The archipelagos share many similar geographical and biological characteristics (Fernández-Palacios et al. 2011). Table 3 reveals the main physical characteristics of the inhabited Macaronesian islands of Portugal and Spain. In some research objectives of this thesis, the four most densely populated islands, São Miguel, Madeira, Gran Canaria, and Tenerife, were designated as the main Macaronesian islands of Portugal and Spain. On these four islands service-related activities employ the majority of the population. Therefore, the tertiary sector is predominant in the active population structure, is the major employer, and accounts for the majority of the working population. Within the tertiary sector, tourism is particularly important.

Table 3. Physical characteristics of the inhabited Macaronesian islands of Portugal and Spain.

Island	Area (km^2)	Highest peak (altitude m)
Corvo	17	Morro dos Homens (718 m)
Flores	141	Morro Alto (914 m)
Faial	173	Cabeço Gordo (1043 m)
Graciosa	61	Caldeira (402 m)
Pico	445	Pico (2351 m)
São Jorge	244	Pico da Esperança (1053 m)
Terceira	400	Serra de Santa Bárbara (1021 m)
Santa Maria	97	Pico Alto (587 m)
São Miguel	745	Pico da Vara (1103 m)
Madeira	759	Pico Ruivo (1862 m)
Porto Santo	43	Pico do Facho (517 m)
El Hierro	269	Malpaso (1501 m)
La Palma	708	Roque de los Muchachos (2423 m)
La Gomera	370	Garajonay (1487 m)
Tenerife	2034	Teide (3718 m)
Gran Canaria	1560	Pico de las Nieves (1949 m)
Fuerteventura	1660	Jandía (807 m)
Lanzarote	846	Peñas del Chache (671 m)

Sources: Instituto Nacional de Estatística (http://www.ine.pt/) & Instituto Canario de Estadística (http://www.gobiernodecanarias.org/istac/).

The Azores archipelago is located between parallels 36°55' and 39°43' latitude North and meridians 25° and 31°17' longitude West. The archipelago has nine islands, all inhabited: Santa Maria, São Miguel, Terceira, Graciosa, São Jorge, Pico, Faial, Flores, and Corvo. The islands span approximately 2323 km², and vary greatly in size with the smallest being Corvo (17 km²) and the largest being São Miguel (745 km²). As of 2013 the population of the Azores almost reached 250 thousand inhabitants. The Azores climate is classified as Köppen-Geiger's Cfb[11] for most of the islands' coastal areas (MSAS & PIM 2012: 19). At sea level the mean air temperature hovers around 17 °C, with an average minimum about 14 °C and an average maximum about 19 °C (MSAS & PIM 2012). The frequent occurrence of rainfall is responsible for the islands' evergreen landscapes. The annual average total precipitation varies from a minimum of 600 mm in Santa Maria up to 3600 mm in Pico's higher altitudes (MSAS & PIM 2012).

With more than half of the Azorean population, São Miguel is the main Azorean island. The island of São Miguel is located between parallels 37°41' and 37°54' latitude North and 25°07' and 25°51' longitude West, it is the largest and most populous island in the Portuguese Azores archipelago. Covering 745 km^2, the island had approximately 140 thousand inhabitants as of 2013. Table 4 reveals that, in São Miguel's southern coastal areas, throughout the year, temperatures range between an average minimum of 11.1 °C and an average maximum of 25 °C. February and August have the lowest and highest average temperatures, respectively, and precipitation is abundant and falls throughout the year, with June and July being the driest summer months.

Table 4. 1971-2000 climate normal for Ponta Delgada, São Miguel.

Lat.: 37º 44' N *Lon.: 25º 41' W* *Alt.: 71 m*	J	F	M	A	MY	JN	JL	AG	S	O	N	D	ANN
Average maximum temperature (°C)	16.5	16.4	16.8	17.4	18.8	21.1	23.7	25	24	21.7	19.4	17.6	**19.9**
Average minimum temperature (°C)	11.5	11.1	11.6	11.9	13.1	15.3	17.2	18.4	17.9	16.1	14.2	12.6	**14.2**
Average total precipitation (mm)	109.2	78.7	87.1	67.2	64.9	40.7	28.7	48.3	97	109.2	120.6	124.7	**976.3**

Source: MSAS & PIM (2012).

The Madeira archipelago is located between parallels 30°01' and 33°06' latitude North and meridians 15°51' and 17°15' longitude west. The archipelago has two inhabited islands (Madeira and Porto Santo), and several uninhabited islets in two sub-archipelagos: the Desertas and Selvagens. Combined, the Madeira Islands span a total surface area of approximately 819 km^2. As of 2013, the archipelago population spread across the two inhabited islands reached almost 270 thousand inhabitants. Madeira is the largest island of the archipelago, covering a surface area of 759 km^2. Across the coastal areas the archipelago's climate is generally classified as Köppen-Geiger's Csb[12] (MSAS & PIM 2012: 19). At sea level the mean air temperature hovers

[11] Maritime temperate with mild summer and no dry season.
[12] Mediterranean with dry and warm summers.

around 19 °C, with an average minimum of about 16 °C and an average maximum of about 21 °C (MSAS & PIM 2012). The annual average total precipitation varies, from a minimum of 300 mm on the island of Porto Santo and up to 2800 mm in Madeira's higher altitudes (MSAS & PIM 2012).

Madeira is the largest island of the Madeiran archipelago. Located between parallels 32°37' and 32°52' latitude North and 16°39' and 17°16' longitude West, it has an area of 759 km^2 and, as of 2013, the island had approximately 260 thousand inhabitants. The island has a very rugged topography dominated by mountains and deep ravines. Altitude reaches 1862 m above sea level (ASL; Table 3). The average altitude is 700 m and 90 percent of the island is over 500 m ASL (Baioni 2011). Across the island steep slopes and abrupt cliffs mark a very rugged terrain and dominate the landscape. Geologically the island is new (< 5 Ma). This allows the landscape to be much more rugged than its neighboring island of Porto Santo which is between 11-14 Ma, and consequently is much more eroded (Fernández-Palacios et al. 2011). Though affected by the same weather systems, the island of Porto Santo is much drier due to the lower average altitude (Santos & Aguiar 2006). On Madeira's densely populated southern coastal areas, temperatures range from an average minimum of 13 °C to an average maximum of 25.9 °C (Table 5). February and September have the lowest and highest average temperatures, respectively. Precipitation tends to be high during the winter months (December through February), whereas in the southern coastal areas the summer months mark a dry season. However, the mountains act as a topographical barrier between the north (windward) and the south (leeward), originating a marked climatic differentiation. Madeira was the first overseas territory to earn an effective occupation by European settlers in the early fifteenth century. According to Baioni (2011), almost 70 percent of the archipelago's population lives across Madeira southern coastal areas, where most of the cities are located and where most of the economic activity takes place. The main urban area is the city of Funchal, which hosts about half of Madeira's population (Neves 2010). In the remaining territory dispersed and fragmented settlements prevail due to a very rugged terrain.

Table 5. 1971-2000 climate normal for Funchal, Madeira.

Lat.: 32º 38' N *Lon.: 16º 53' W* *Alt.: 58 m*	J	F	M	A	MY	JN	JL	AG	S	O	N	D	ANN
Average maximum temperature (°C)	19.2	19.3	19.8	19.9	20.9	22.6	24.4	25.8	25.9	24.4	22.4	20.4	**22.1**
Average minimum temperature (°C)	13.2	13	13.3	13.8	14.9	16.9	18.4	19.4	19.4	18	16.1	14.5	**15.9**
Average total precipitation (mm)	90.6	64.5	56.2	37.8	30.3	6.4	2.8	3.1	34.7	78.2	82.4	109.4	**596.4**

Source: MSAS & PIM (2012).

The Canary Islands are located between parallels 27°38’ and 29°17’ latitude North and 13°24’ and 18°10’ longitude west. The archipelago occupies a total surface area of approximately 7447 km² distributed across seven inhabited islands and several small islets. Across the archipelago the population totaled 2.2 million inhabitants as of 2013 and is predominately concentrated on the islands of Tenerife and Gran Canaria. The archipelago climate along the coastal areas is mostly classified as either Köppen-Geiger’s BWh[13] or Csb[14] (MSAS & PIM, 2012: 19). At sea level the mean air temperature hovers around 21 °C, with an average minimum of about 19 °C and an average maximum of about 23 °C (MSAS & PIM 2012). The annual average total precipitation varies from a minimum of less than 100 mm in the southern arid coastal areas of Tenerife and Gran Canaria up to 1200 mm in La Palma’s higher altitudes (MSAS & PIM 2012). The eroded islands of Fuerteventura and Lanzarote are among Europe’s most arid areas. On these two islands Hernández-Moreno et al. (2007) highlighted a low annual rainfall total (< 150 mm), a high inter-annual variability, and prolonged droughts.

Across the archipelago Gran Canaria and Tenerife are the most densely populated islands and have made significant anthropogenic impacts on their landscapes. Gran Canaria has a surface of 1560 km² located between parallels 27°44’ and 28°10’ latitude North and 15°21’ and 15°50’ longitude West. As of 2013, it is the second most populous island of the Canary Islands, with approximately 850 thousand inhabitants. Table 6 shows that along the northeastern coastal areas, temperatures range from an average minimum of 14.7 °C to an average maximum of 27.1 °C. January and August/September have the lowest and highest average temperatures, respectively. Precipitation is low throughout the year and practically nonexistent in the dry summer months. However, its distribution is uneven throughout the island and some areas are much drier than others.

Table 6. 1971-2000 climate normal for Gran Canaria Airport, Gran Canaria.

Lat.: 27º 55’ N *Lon.: 15º 23’ W* *Alt.: 24 m*	J	F	M	A	MY	JN	JL	AG	S	O	N	D	ANN
Average maximum temperature (°C)	20.6	21	21.8	22.1	23.1	24.7	26.5	27.1	27.1	25.8	23.9	21.8	**23.8**
Average minimum temperature (°C)	14.7	14.9	15.4	15.7	17	18.7	20.4	21.2	21.2	19.7	17.9	15.7	**17.7**
Average total precipitation (mm)	18.2	24.1	13.9	7.3	1.6	0.3	0.2	0.1	10.4	12.8	17.9	27.4	**134.2**

Source: MSAS & PIM (2012).

Tenerife is located between parallels 27°59’ and 28°36’ latitude North and 16°06’ and 16°55’ longitude West. It is the largest and most populous of the Canary Islands, with a surface

[13] Arid.
[14] Mediterranean with dry and warm summers.

area of 2034 km², and approximately 900 thousand inhabitants as of 2013. Table 7 shows that, across the northeastern coastal areas temperatures range from an average minimum of 15.1 °C to an average maximum of 28.8 °C. The months of January/February and August have the lowest and highest average temperatures, respectively. In the coastal areas precipitation is slightly higher than in Gran Canaria. Nonetheless, the pluviometric regime is equally marked by noticeable dryness in the summer months, although its distribution is very uneven throughout the island.

Table 7. 1971-2000 climate normal for Santa Cruz de Tenerife, Tenerife.

Lat.: 28º 27' N Lon.: 16º 15' W Alt.: 35 m	J	F	M	A	MY	JN	JL	AG	S	O	N	D	ANN
Average maximum temperature (°C)	20.6	20.9	21.7	22.3	23.7	25.7	28.3	28.8	27.9	26	23.9	21.8	**24.3**
Average minimum temperature (°C)	15.1	15.1	15.6	16.2	17.5	19	20.8	21.4	21.3	20	18.1	16.2	**18**
Average total precipitation (mm)	34.2	35.6	28.9	14	4.3	0.8	0.1	0.6	6.3	17.7	27.2	44.4	**214.1**

Source: MSAS & PIM (2012).

Climatically, the Macaronesian islands of Portugal and Spain span a transition zone between a temperate and a subtropical climate, with mild temperatures and very low seasonal variation in temperatures (Cropper & Hanna 2014). Across the eighteen inhabited islands, there is a climate variation because of the latitudinal distribution of the archipelagos (de Nicolás et al. 1989). Cropper and Hanna (2014) identify that the regional climate is influenced by the semi-permanent Azores high-pressure system, prevailing northeasterly trade winds, and the surrounding oceanic currents. However, because of their volcanic origin, due to altitude, aspect, and slope, very different microclimates can be found (de Nicolás et al. 1989). In fact, on the island of Tenerife, which spans only 2034 km^2, eight Köppen-Geiger climate classifications are found (Table 8).

Table 8. Köppen-Geiger's climate classification on the main islands.

		São Miguel	Madeira	Gran Canaria	Tenerife
Dry climates: Type B	BWh (hot arid)			•	•
	BWk (cold arid)				•
	BSh (hot steppe)			•	•
	BSk (cold steppe)			•	•
Temperate climates: Type C	Csa (Mediterranean with hot and dry summer)	•	•	•	•
	Csb (Mediterranean with cool and dry summers)	•	•	•	•
	Csc (Dry-summer maritime subalpine)		•		•
	Cfb (Maritime temperate with mild summer and no dry season)	•			
Cold climates: Type D	Dfc (cold without a dry season and a fresh summer)				•

Source: Adapted from MSAS & PIM (2012).

Across Macaronesia, the landscapes are very heterogeneous given the archipelagos' volcanic origins, and the orography creates a diversity of microclimates and landscapes, ranging from arid areas to humid evergreen forests. This landscape diversity is particularly present in the mountainous islands such as Madeira, Gran Canaria, and Tenerife. According to Baioni (2011), exposure to dominant northerly and northeasterly winds are fundamental in explaining the landscape differentiation between the northern and southern sides on the mountainous islands. Nonetheless, despite the variability among the islands, the three archipelagos fall into the same biogeographical region of Macaronesia, which also includes the archipelago of Cape Verde, an African country not covered in this research.

Overall, across the archipelagos the landscape differentiation among the islands essentially arises from three factors: (1) the amount of precipitation, (2) the types of volcanic eruptions that created the islands, and (3) the different states of erosion coinciding with the geological age of each island. It is important to note that in geological time these archipelagos are very recent (< 30 Ma). Their origins reside in successive submarine volcanic eruptions from fractures and zones of weakness on the Atlantic oceanic crust (Fernández-Palacios et al. 2011). Consequently, the islands are principally composed of igneous rocks with volcanic structures and pyroclastic debris comprising the majority of the archipelagos. The volcanic activity in these islands generated some of the highest sea cliffs and island peaks in the world. Volcanism is now extinct in Madeira but is still active in the Azores and the Canaries across several islands including several eruptions within the last decades (Fernández-Palacios & Dias 2001).

The most important ecosystem in the Macaronesia biogeographical region is the Atlantic laurel forest, which develops in areas with very low seasonal temperature variation and high precipitation. The ecological importance of the laurel forests relies on its vegetation being composed of the remnants of "*Palaeotropical geoflora*" (Fernández-Palacios et al. 2011: 232), a flora that thrived in the Paleogene Period (c. 64–25 Ma) after the Cretaceous–Paleogene extinction event. Having been wiped out from the rest of the continent because of the Quaternary glaciation, Europe's last impoverished remnants of *Palaeotropical geoflora* survived in these archipelagos and were able to subsist where the impact of the Quaternary climate change was moderated by the oceanic influence (Barrón & Peyrot 2006; Rodríguez-Sánchez & Arroyo 2008; Fernández-Palacios et al. 2011). Consequently, due to their ecological importance (Sundseth, 2009), and their vulnerability to anthropogenic impact, these islands demand LULC studies.

3.2. LULC studies about the Macaronesian islands of Portugal and Spain

There are numerous works on the Macaronesia region. As of 2016, a "Google Scholar" search with the word "Macaronesia" resulted in about 11000 results. However, the vast majority of the geographical studies address ecology (Illera et al. 2012), climatology (Cropper & Hanna 2014), biogeography (Valido et al. 2004), geomorphology (Scheidegger 2002), and tourism (López & García 2009). Regarding LULC studies, the extant research about Macaronesia lacks in comparative studies and is focused on individual islands (Schweichel 1999; Keuchel et al. 2003; Otto et al. 2007; Günthert et al. 2011; Pla 2014). As previously mentioned, one of the main issues hampering LULC research across the region is the lack of comparable data sources for the islands. For example, the Azores joined the CORINE Land Cover project in 2011 and data became available in 2013. As a result, only recently was it possible for researchers to access a compatible LULC database for all the Macaronesian islands of Portugal and Spain. Nonetheless, the available scale is still very coarse (25 ha of minimum mapping unit).

The treaty of Lisbon[15] has included territorial cohesion alongside economic and social cohesion as a strategic objective for the EU. One of the main issues related to territorial cohesion is the need for data on different territorial levels, particularly for lower geographical levels (EUROSTAT 2012). Nonetheless, on these islands the existing available geospatial data solutions do not conform to the need for European data on different territorial levels on a trans-regional and trans-border perspective. The only comparable LULC data available for all the islands studied are the CLC datasets. However, CLC has a limited scale for more detailed studies. Since there are no compatible high-resolution LULC datasets for the study areas, in order to answer the fifth research question, this research proceeds to a high-resolution settlement mapping for the four main islands. The final step in this research has the goal of creating a high-resolution dataset of the main islands' settlements, while providing a methodological basis for the classification of settlement patterns, thus addressing the islands' lack of uniform and comparable data.

As of 2016, and to the best of the author's knowledge, none of the extant research about LULC addresses more than one Macaronesian archipelago. Nonetheless, although resorting to different methods and data sources, the extant LULC studies about the Macaronesian islands allow a general LULC characterization of the archipelagos.

According to Calado et al. (2015), the occupation of the Azores has similar patterns in all the islands of the archipelago, so much so that the presence of agricultural areas and pastures predominates throughout the archipelago. Focusing on the archipelago's land cover, Borges et

[15] Signed by the EU member states on 13 December 2007, it amends the Treaty of Rome (1958), and the Maastricht Treaty (1993), the two treaties that form the constitutional basis of the EU.

al. (2009) corroborate the same claim and identify pastures as the predominant category of land cover throughout the Azorean islands. Calado et al. (2015) resorted to a land cover map of the Azores with a minimum mapping unit of 1 ha represented by a nomenclature with nine classes (Cruz et al. 2007). In another study, Cruz et al. (2007) note that agricultural areas and pastures occupy more than half of the archipelago (14 and 42 percent, respectively). According to Cruz et al. (2007), pastures are most prevalent on the island of Faial (52 percent, while agricultural areas are most prevalent on the island of Graciosa (35 percent), more than twice the regional average. Calado et al. (2014) note that, because of the better soil, agricultural areas are also dominant on the islands of Faial, Terceira, and São Miguel. It is important to note that the agrarian structure in the Azores is based on small properties, and agricultural systems in the Azores are mostly based on pastures for direct grazing in a rotation with maize silage[16] (Fontes et al. 2004). According to Borges et al. (2009), about 68 percent of the farms have less than 5 hectares, and only 2 percent have more than 50 hectares. Borges et al. (2009) also draw attention to other islands, such as Pico and São Jorge, where agriculture areas are less dominant and are occupied by natural areas. According to Cruz et al. (2007), forest and natural vegetation combined occupy about 35 percent of the Azores archipelago (22 percent and 13 percent, respectively). Nonetheless, the authors note that forested areas on the islands of Pico and São Jorge (about 33 percent and 26 percent, respectively) heavily influence the regional average (Cruz et al. 2007). In fact, Borges et al. (2009) draw our attention to the islands of Graciosa and Corvo, which are virtually deforested despite having vast semi-natural areas. According to Borges et al. (2009), the areas with the largest collection of natural vegetation with little intervention are located on the islands of Terceira, Pico, and Flores. Finally, according to Cruz et al. (2007), urban areas occupy about 5 percent of the archipelago, with concentrations in Terceira (8 percent), Santa Maria (7 percent), and São Miguel (6 percent), being the highest and the concentrations on the islands of Flores and Corvo being the lowest (two and one percent, respectively).

Focusing on Madeira, Neves (2010) notes that forested areas occupy 56 percent of the island, followed by natural areas (23 percent), and agricultural areas (18 percent). It is important to note that, because of the rugged terrain, Madeira's agrarian structure is marked by very small properties. According to Santos and Aguiar (2006), the average size of operational holdings is about 0.4 ha. Additionally due to the rugged terrain, most of the cultivated areas are agricultural terraces. According to Baioni (2011), from 1986 to 1991, the cultivated surface area decreased about 20 percent. Agricultural areas are mainly concentrated on the southern and eastern coasts where the best climatic conditions occur and mist and fog are less frequent. As a result, most

[16] Maize silage is important for feeding the herds on the farms.

crops are irrigated due to reduced precipitation in the areas of greatest agricultural potential (Santos & Aguiar 2006).

In the Canary Islands, and according to data from CEUS (2012), the majority of the archipelago is occupied by forests and natural areas (72 percent), followed by agricultural areas (23 percent). Artificial surfaces occupy about 5 percent of the territory. According to Domínguez Mujica and Díaz Hernández (2005), the Canaries' cultivated area amounted to 19 percent of the territory in the middle of the last century. Currently only about 6.7 percent of the archipelago's surface is cultivated. This process of agricultural abandonment has been coupled with an increase of forested area due to natural recovery associated with the recession of agricultural areas and numerous reforestation campaigns. In fact, in 1992 forests occupied 14 percent of the archipelago, whereas ten years later they occupied about 18 percent (CEUS 2012). Different reforestation campaigns have contributed to a significant increase in forest area on the Canary Islands. It is estimated that between 1980 and 2002 about 2875 ha were reforested in the archipelago, 1585 ha between 2004 and 2008, and 395 ha between 2009 and 2011 (CEUS 2012).

Across the mountainous islands relief, altitude, and aspect play a crucial role, particularly in defining natural land cover, which reflects the biophysical conditions along the altitudinal gradients. This is best exemplified in the most mountainous of the Macaronesia islands: Tenerife. In fact, in Tenerife, Keuchel et al. (2003) found a high correlation between land cover and altitude. Madeira is another good example of the correlation between altitude and land cover. According to Prada et al. (2009), in Madeira a cloud belt of orographic origin persists for more than 200 days per year between the 800 and 1600 m ASL. This cloud belt is crucial for Madeira's forests (Prada et al. 2009). In order to further the analysis about the relationship between land cover and altitude, in the third research objective, this thesis addresses the altitudinal zonation on the main Macaronesian islands of Portugal and Spain.

Shifting the focus to land use, Otto et al. (2007) analyzed the land use changes between 1964 and 1992 on the southernmost part of Tenerife, an area where, according to the authors, the conflicting interests of tourism, agriculture, and the protection of nature were especially pronounced during the past decades. In the authors' study area (Otto et al. 2007) in 1964, buildings and infrastructure occupied only 22 ha of the study area, as compared to 496 ha in 1992. The authors draw attention to the fact that in 1964, 56 percent of the study area was covered by natural vegetation, and most of the landscape was not cultivated because of the infertile soils and the extremely arid conditions. By 1992, 45 percent of this endemic-rich vegetation had been destroyed. Ultimately, 41.7 percent of the study area had been severely transformed during the 28 years between 1964 and 1992 (Otto et al. 2007).

3.3. The driving forces of land use on the Macaronesian islands of Portugal and Spain

This section focuses on land use driving forces. This is because, while human activity defines land use, land cover change can proceed with or without a proximal human driver (Brown et al. 2012). Land cover is dependent upon biophysical and anthropogenic interactions. Therefore, land cover change is more complex and less easily explained when compared with land use change. Consequently, this section focuses on anthropogenic driving forces, the human activities defining and changing land use.

3.3.1. Farming-related pressure

There were aboriginal inhabitants in the Canaries long before European colonization in the fifteenth century. The "Guanches," descendants from Northern African peoples, were believed to have migrated to the archipelago as late as 2500 years ago (Rando et al. 1999). Because of their Neolithic civilization, their anthropogenic impact on the landscape was small, albeit "the use of fire by the Guanche people, together with the introduction of goats, sheep, pigs, and rodents had a heavy impact on the vegetation" (Fernández-Palacios et al. 2011: 241). On the contrary, the Portuguese archipelagos were uninhabited prior to colonization in the fifteenth century. For this reason the Portuguese islands have a unique feature – about 600 years ago, they were the last European landscapes directly exposed to the anthropogenic influence of humankind.

Since colonization, the islands' geography influenced all human activity. In fact, the terrain and soil productivity were the historical reasons for the location of settlements, along with the proximity to natural harbors. The fertile volcanic soils, further enriched with depositions of tephra[17] and a favorable climate, allowed a rapid expansion of the agricultural areas across the islands. Every available parcel of land with a moderate slope was cultivated, because the mild climate allowed for the easy cultivation of very high-value agricultural commodities (e.g. sugarcane) which were difficult to cultivate on the much cooler mainland (Moore 2009). As a result, the exportation of high demand products, such as sugar and wine, fueled the islands' rampant economic development during the fifteenth and sixteenth centuries. The limited agricultural land, together with the presence of steep slopes on the mountainous islands, were the causes for the construction of the agricultural terraces that have transformed the landscape of the islands (Hernández-Moreno et al. 2007). Generally, the islands' rugged

[17] Fragmental material produced by a volcanic eruption.

terrain prohibits large-scale agriculture. Therefore, to gain more usable land and provide cultivable hillsides of steep mountainous slopes, the people of the islands have extensively used cultivation terraces. These manmade terraces along the slopes allowed the people of the islands to cultivate sloped and mountainous land, thus allowing the agricultural areas to extend up to their altitudinal lapse rate[18] limits. As a result, agricultural areas were no longer constrained to coastal lowlands.

Therefore, from the beginning of the colonization process, these islands suffered significant anthropogenic landscape changes, namely from the intensive and continuous change of forests into plantations (Moore 2009). The lush evergreen forests were cut, and the areas with moderate slopes were deforested. The main goal was not timber or other wood related products, but rather to clear the terrain for agriculture areas. According to Moore (2009), on the island of Madeira[19] the forests were so dense that the first settlers had to burn the vegetation to open up clearings. In the Azores, since the beginning of the colonization in the early fifteenth century, the economy relied almost exclusively on agricultural activities like other archipelagos of the region. Initially the Azores relied on cereal and fruit tree farming along the coastal areas, while the inland was used for livestock. This structure prevailed across different economic cycles until the mid-twentieth century when agricultural cultivations and the thriving livestock and dairy production sectors started to mechanize. This would profoundly change the Azores landscape in the twentieth century, despite the progressive rise of the tertiary sector. The Canary Islands also underwent drastic landscape changes. Especially on the more humid and fertile windward slopes on the mountainous islands, where large areas of forests were cut to open up clearings for agricultural activities (Otto et al. 2007). In the Canary Islands, just like in the other Macaronesian archipelagos, up to the mid-twentieth century land used for farming and grazing were the leading causes of deforestation (Hernández-Moreno et al. 2007).

This massive deforestation of the archipelagos due to farming-related pressure had different intensities among and even within the islands because the very sloped and rugged areas were impossible to cultivate. Thus, nowadays the best-preserved native forests can still be found in these inaccessible areas. On the islands' drier areas where forests were absent, agricultural activities were also much more challenging. As a result, these dry ecosystems were mostly undisturbed up until the twentieth century. According to Otto et al. (2007), along the dry southern coastal areas of the Canary Islands, land use changed little over the centuries. During the past decades, however, these semi-arid coastal landscapes have been transformed dramatically by mass tourism and modern irrigation-based agriculture (Otto et al. 2007).

[18] The decrease of atmospheric temperature with an increase in altitude (about 6 °C/km).
[19] The island gained the name from the lush forests. Madeira is the Portuguese word for "wood".

According to Hernández-Moreno et al. (2007), socio-economic changes have led to an overall reduction in agricultural areas, especially ones that formerly used traditional practices. However, many agricultural areas have been replaced by intensive and less environmentally friendly farming, namely irrigation-based intensive cultivations. Therefore, although in the last decades a clear phenomenon of agricultural abandonment had occurred, leading to a drastic decrease of non-irrigated cultivations, nowadays there is a prevalence of irrigated areas due to the shift to intensive cultivations (CEUS 2012).

After shaping the slopes of the mountains through the construction of agricultural terraces, the agricultural abandonment of the last decades contributed to greater flood hazards across the islands. This is a consequence of the degradation of the retaining walls of the cultivation terraces. These cultivation terraces allowed the people of the islands to cultivate sloped and mountainous land. When the terraces were in good condition, rainwater had time to infiltrate because the slope was minimal. Without proper terrace maintenance, most of the precipitation water runs off very quickly down the steep slopes of the mountainous islands. In fact, floods and landslides are the main natural hazards in this region and have claimed several lives in the last decade alone. The most significant recent occurrence in the region was the Madeira floods on February 20th, 2010. The floods killed 42 people, 120 injured, and displaced more than 200 people (Baioni 2011).

Overall, a common feature of the Macaronesian islands is that, in the past agricultural activities were almost exclusively responsible for shaping the islands' landscapes because of small settlements and lack of a meaningful secondary sector. Over a period of five centuries, this farming-related pressure was responsible for major incursions into the islands' natural areas. Consequently, ever since European colonization in the fifteenth century and up until the mid-twentieth century, anthropogenic land change was predominately attributable to agricultural activities consuming forests and natural areas. In the mid-twentieth century, owing to profound social and economic changes, the tertiary sector started its rise to become the main economic sector. Because the secondary sector in this region has always been minor, this substantial shift to the tertiary sector dictated a progressive abandonment of the primary sector. Hence, agricultural areas started to recede. As a result, the last decades of the twentieth century were marked by a significant shift in LULC dynamics. Agricultural activities ceased to be the main driving force behind land change and were replaced by the rampant increase of artificial surfaces.

3.3.2. Arson forest fires

As mentioned, due to the archipelagos isolation from Europe's mainland and the moderating effect of the Atlantic Ocean, some remnants of *Palaeotropical geoflora* were able to survive the Quaternary glaciation and endured on these islands in the areas of laurel forest. However, anthropogenic impact through cultivation, livestock and introduced species, irreversibly degraded the islands rich biotas. In fact, human colonization dramatically decreased the laurel forest coverage from its original area. According to Fernández-Palacios et al. (2011), Gran Canaria has only one percent of its original laurel forest, whereas Madeira has the largest existing area about 15000 ha. Nonetheless, this is only 25 percent of its potential prior to human colonization. Because of the high annual average total precipitation (> 600 mm), the Azores have by far the highest potential area for the laurel forest. Even so, because of the intensive land use change into agricultural areas, the archipelago has only about 6000 ha of laurel forest, only 3 percent of its potential (Fernández-Palacios et al. 2011). Nowadays, in all the islands, the best remaining formations of the Macaronesian laurel forest are well protected from land development pressure through several ecological reserves (Santana et al. 2006). Although protected, introduced species and wildfires remain a severe threat. In fact, fire is a major driver of land change in these islands.

It is important to note that, despite being mostly in protected areas, recurring burning has destroyed several forest areas that transitioned to open spaces with little or no vegetation. Some of these fires were natural wildfires, but many were caused by arson. Another factor to consider in the destruction of the forests over the years is its contribution to an increased flood hazard. Despite having a natural cause (i.e. extreme weather events), flooding across the islands has increased in the last decades due to continuous land development on flood-prone areas, coupled with deforestations through burning, thus worsening soil erosion and raising the runoff coefficient (Baioni 2011).

3.3.3. Demographic pressure

The economic cycles accompanying the islands' agricultural production were inextricably linked to the demographic dynamic. After colonization, the need for agricultural laborers attracted a large contingent population from Europe's mainland. Up to the mid-twentieth century, the archipelagos shared a similar demographic dynamic. After an initial colonization period in the fifteenth century, the positive agricultural economic cycles attracted new people, whereas during recessions the islands lost significant contingents of people through emigration (mainly to North and South America). During the twentieth century this dynamic started to change. Accompanying the gradual improvement of the living conditions, the Azores and Madeira substantially decreased their historic emigration rates. Furthermore, the Canaries became a significant destination for immigrants in search of the opportunities that the booming tourism sector started to create.

A comparison of the population density among the islands reveals striking differences among the archipelagos (Table 9). It is important to note that, the primary sector had traditionally accounted for most of the islands' economic activity, although currently there is a much lower concentration of activity in the primary sector, and the vast majority of the active population is employed in the tertiary sector.

Table 9. Demographic statistics of the Macaronesian islands of Portugal and Spain.

	1991		2000		2006		2013	
	Pop.	**inhab./ km²**	**Pop.**	**inhab./ km²**	**Pop.**	**inhab./ km²**	**Pop.**	**inhab./ km²**
Corvo	392	23	423	25	415	24	463	27
Flores	4347	31	3998	28	3893	28	3763	27
Faial	15029	87	15042	87	15066	87	14994	87
Graciosa	5207	86	4791	79	4562	75	4400	73
Pico	15263	34	14826	33	14448	32	14101	32
São Jorge	10357	43	9659	40	9450	39	8777	36
Terceira	56037	140	55769	139	56509	141	56641	142
Santa Maria	5910	61	5575	58	5588	58	5663	58
São Miguel	127442	171	131304	176	135740	182	138638	186
Azores archipelago	**239984**	**103**	**241387**	**104**	**245671**	**106**	**247440**	**107**
Madeira	248865	328	239688	316	255969	337	256014	338
Porto Santo	4728	111	4462	105	5110	120	5299	124
Madeira archipelago	**253593**	**317***	**244150**	**305***	**261079**	**326***	**261313**	**326***
El Hierro	7162	27	8533	32	10688	40	10979	41
La Palma	78867	111	82483	117	86062	122	85115	120
La Gomera	15963	43	18300	49	21952	59	21153	57
Tenerife	623823	307	709365	349	852945	419	897582	441
Gran Canaria	666150	427	741161	475	807049	517	852723	547
Fuerteventura	36908	22	60124	36	89680	54	109174	66
Lanzarote	64911	77	96310	144	127457	151	141953	168
Canaries archipelago	**1493784**	**201**	**1716276**	**230**	**1995833**	**268**	**2118679**	**285**

**Note: the area of the uninhabited sub-archipelagos of Desertas and Selvagens are not included.*

Source: Instituto Nacional de Estatística (http://www.ine.pt/) & Instituto Canario de Estadística (http://www.gobiernodecanarias.org/istac/).

The Azores is by far the least populated archipelago, and as of 2013 some islands had less than 30 inhab./km² (e.g. Corvo and Flores). On the other hand, in the same year, Madeira, Gran Canaria and Tenerife stand out with 338, 547 and 441 inhab./km² respectively. These three islands were agriculturally the richest, and controlled a large part of the exporting agriculture that in the past made up the majority of the economic activity in this region. By having major ports where the agricultural produc left for foreign markets and multiple urban functions, these islands generated jobs that attracted strong immigration (Ruiz, 1990). This largely explains the concentration of population on these three islands, whereas the small size and lack of economic prospects led the remaining islands to have much lower population densities (Table 9).

Table 9 shows that the transition into the twenty-first century was marked by distinct demographic dynamics across the archipelagos. Overall, the largest islands recorded the most significant growth rates, whereas, the smaller islands are marked by much lower growth rates. The Azores had several islands losing population over the last two decades. Flores, Graciosa, Pico, São Jorge, and Santa Maria all have decreasing populations (Table 9). Conversely, during the last two decades, São Miguel, the most populous Azorean island with more than half of the Azorean population, registered a modest increase of 15 inhab./km^2. The years between 1991 and 2013 experienced little change in the population density on the island, going from 171 to 186 inhab./km^2 (Table 9). Due to the extreme dependency on the primary sector, and the difficulty in sustaining an increasing population, São Miguel was responsible for a large contingent of Portuguese emigration mainly to Brazil, the United States, and Canada. However, over the last decades, the population density reveals a relatively stable trend (Table 9), standing at about 186 inhab./km^2. With a much higher population density, the island of Madeira was marked by a very modest increase: a growth of 10 inhab./km^2 over a period of 22 years. Madeira's population density reveals a distinct trend over the last two decades (Table 9). The 1990s were signaled by a loss of population, 328 to 316 inhab./km^2, whereas the next decade experienced an increase from 316 to 338 inhab./km^2. Like São Miguel, Madeira was vulnerable to agricultural economic cycles and responsible for a large contingent of Portuguese emigration. Madeiran immigrants' main destinations were Brazil, the United States, South Africa, and Venezuela.

In contrast, the Canaries experienced greater population changes, namely on the islands of Gran Canaria and Tenerife whose populations both became denser in the last two decades by more than 100 inhab./km^2. This marked demographic change was due to immigration attracted by the economic opportunities of the thriving tourism sector (Guerra Talavera & Garcia 2008). Even so, the archipelago still has islands, such as La Palma, which increased its population density by only 9 inhab./km^2 because of a lack of economic prospects. This increase is the lowest demographic change in the Canaries over the last two decades (Table 9). Focusing on the main islands, Gran Canaria's population density has grown considerably over the last two decades (Table 9). The years between 1991 and 2013 experienced strong population increases, going from 427 to 547 inhab./km^2. Over the last two decades, Tenerife's population density experienced a trend similar to Gran Canaria's (Table 9). The years between 1991 and 2013 experienced a marked population increase, going from 307 to 441 inhabitants/km^2. Because of the dependency from the primary sector and the same economic difficulties faced by the other islands in this region, Tenerife was responsible for a large contingent of Spanish emigration to

Latin America, mainly to Cuba and Venezuela. In the last decades, because of ever-increasing tourism activities, the migration flows reversed, and Tenerife received an influx of immigrants that nowadays make the island the most populous of the Macaronesian islands with almost 1 million inhabitants.

Overall, all the eighteen inhabited islands across these three archipelagos shared the disproportionate dependency on the primary sector since their colonization up until the mid-twentieth century when the tertiary sector started to grown steadily (though to varying degrees among the archipelagos and islands). Thus, the last decades registered a sharp decline in primary economic activities and a shift to tertiary activities. In the archipelagos tourism is now particularly important, and have promoted a major expansion of the tertiary sector. Regarding the Canary Islands, Otto et al. (2007) note that this economic development led to large-scale social changes such as increasing immigration, rapid increases in the local population, and the abandonment of traditional agricultural activities. In fact, based solely on immigration, certain tourist municipalities doubled or even triple their population between 1991 and 2001 (Márquez 2007). According to Márquez (2007), this had social costs, caused significant gaps in infrastructure and services, and significantly affected the environment. Another key aspect of this dynamic on the main Canary Islands is the intra-islands dynamic. Since the mid-twentieth century, the north and inland of Gran Canaria and Tenerife started losing population who were moving to the south (Ruiz 1990). This was the result of the consolidation of the tourism model, which attracted people from the north and inland towards the coastal southern areas (Alonso et al. 2005). As a result, in the Canaries there has been an internal adjustment of the population because of economic changes (Ruiz, 1990). This process has not occurred in Madeira because over the years its tourism-related activity remained located in the city of Funchal in the south and there has been no seaside resort development elsewhere on the island. Calado et al. (2011) have drawn attention to the promotion of social and economic growth, which in turn has resulted in accelerated coastal development. Regarding this development, Calado et al. (2011) list two reasons why the environmental impacts on coastal systems have been overlooked: the rush for developers to cater to lucrative real-estate demands and lax monitoring plans.

Overall, the demographic data (Table 9) highlights that, apart from some Canary Islands (e.g. Gran Canaria, Tenerife, and Lanzarote), demographic pressure was not a significant driving force behind land use. Even on the islands where population growth was most extreme, certain Canarian municipalities' increase in artificial surfaces has exceeded the corresponding population growth by more than six times according to data from CEUS (2012) from 2001 to 2007. In fact, Table 9 demonstrates that the majority of the islands had a modest population change over the last decades. The Azores even had several islands with decreasing populations. However, the data used to answer the first research question will show that, across the islands of the three archipelagos, the distribution of artificial surfaces has increased dramatically in recent decades. Thus, there are other land use driving forces responsible for much of the land use change occurring over the last decades. Among these driving forces, tourism-related and real estate pressure are the main land use driving forces in this region.

3.3.4. Tourism-related and real estate pressure

Because of the climate, the Macaronesian islands of Portugal and Spain have long been considered attractive for tourism. The first tourism phase in the region began in the late nineteenth century went until the mid-twentieth century (Guerra Talavera & Garcia 2008). Despite its economic importance, the anthropogenic impact of this phase was low since it was aimed at a small wealthy elite. The second phase occurred from the 1960s onwards. This phase corresponded with the development of mass tourism in Europe (Guerra Talavera & Garcia, 2008). The post–World War II economic expansion allowed real estate and tourism-related activities to flourish (Miller & Ditton 1986). In this region tourism gradually increased over the twentieth century to high levels. Tourism especially increased in the Madeira and Canary archipelagos, whereas a rainy climate and a further distance from the mainland prohibited the Azores from becoming a mass tourism destination. The Azores have never been a mass tourism destination. Nevertheless, the 2015 launch of low cost flight connections to Portugal's mainland has started attracting an increasing number of visitors.

In the late nineteenth century, a small number of wealthy foreign tourists started to visit the Madeira and Canary islands because of their mild climate and proximity to Europe's mainland. Initially the emphasis of tourism was on the mild climate's ability to treat health issues and tourism concentrated in the main cities. However, the economic prosperity of the second half of the twentieth century allowed for the advent of mass tourism, which led to tremendous economic and social transformations and ultimately transformed the islands' landscapes. Moreover, the last decades of the twentieth century promoted the attraction of "sun, sand, and sea," which thereby created the tourism-related boom of Gran Canaria's and Tenerife's southern coastal areas. This process has been felt much more intensely on the Spanish islands, because the island of Madeira has no sandy beaches. In the Canaries, Simancas Cruz et al. (2011) estimate the growth rate of the tourist accommodation between 1987 and 1993 at 34.6 percent, whereas between 1995 and 2000 the rate was 9.3 percent. The authors also estimate that, between 1998 and 2009, the growth rate of the area occupied by tourism-related facilities across the most touristic Canary Islands (i.e. Tenerife, Gran Canaria, Fuerteventura, and Lanzarote) was 56.6 percent (Simancas Cruz et al. 2011). A direct consequence of this development was the drastic transformation of the islands' coastal landscapes. Along the Canaries' semi-arid southern coastal areas, land use changed little over the centuries. However, during the past decades these semi-arid coastal landscapes have been transformed dramatically by mass tourism (Otto et al. 2007).

Over the twentieth century Madeira also became an important European tourism destination, with the majority of the tourism-related activity concentrated in the south, in the city of Funchal. The last decades of the twentieth century marked a sharp increase in land development pressure, mainly on the southern coastal areas where tourism-related activities are a major impact on the landscape (Borges et al. 2009). After irreparable damages to the landscape, the stakeholders elected a sustainable tourism model based on the natural landscape, complemented by contact with the history, culture, gastronomy, and wines of the region (CCIM 2015). The sustainable tourism model intended for the archipelago is incompatible with the twentieth century paradigm of mass concentrations of tourists.

Across Macaronesia the unceasing expansion of agricultural areas across five centuries, exacerbated by the tourism and speculative real estate pressure of the last decades, contributed to an increasing anthropogenic landscape. This is clearly visible along the coastlines of the most populous islands where the continuous land development pressure of the last decades, aggravated by institutional passivity neglecting the good practices of spatial planning, led to environmental degradation, especially in coastal areas, the most desirable for real estate and tourism. On these islands the coastal areas concentrate the majority of the artificial surfaces and land development pressure along the coast. As a result, on the main islands the establishment of hotels and other tourism-related facilities has made negative impacts on the natural coastal areas. Consequently, the coastal strip of these islands has experienced a rapid transformation. The land development pressure for building residential and tourism-related infrastructure and the lack of efficient land use planning strategies have had a tremendous impact on the islands' coastal areas. The impact of this transformation has been recorded in LULC data, as will be shown when answering the second research objective.

The Canaries have a peculiar feature worthy of research. Tourism is the most prominent economic activity on these islands, responsible for "at least 50 % of the GDP (80 % according to some authors)" (Garín-Mun 2006: 282) and therefore makes the archipelago one of Europe's major tourism destinations. Certain research regards economic forces as the dominant influence on change (Guy & Henneberry 2000; Bürgi et al. 2004). As mentioned, over the past few decades, the largest Canary Islands have undergone an intense land change process originating in tourism-related activity, and a rapid population growth through economic-related immigration (Guerra Talavera & Garcia, 2008). Consequently, the development of tourism, which especially impacted the south of the islands in the 1960s, and the crisis in the traditional primary sector have shifted the distribution of human resources in both Gran Canaria and Tenerife. Due to orographically induced adiabatic cooling that creates a cloud belt responsible for orographic precipitation, the windward north has worse weather than the south. Moreover, because of the trade winds, the north also has strong waves and currents. Consequently, seaside resorts are concentrated in the Canaries' dry southern coastal areas (Guerra Talavera & Garcia 2008).

In the Canaries, "sun, sand, and sea" tourism was well-developed in the last decades of the twentieth century mainly on the islands of Tenerife and Gran Canaria. However, mass tourism was concluded to be a clearly unsustainable model (Rodríguez et al. 2008). Therefore, similarly to what has been observed in other places (Ioannides 2002), the concern with tourism sustainability led to alternative models other than "sun, sand, and sea" is became an opportunity for sustainable tourism in the Canary Islands. Nowadays, one of the main strategic lines of tourism development in the Canaries envisions the development of a sustainable tourism balancing the economic objectives of tourism development with the maintenance of landscape resources (López & García 2006). It is important to note that, tourism development and its associated commercial and residential growth and real estate speculation, dramatically changed the islands' landscapes. Regarding the research questions of this thesis, this change has been recorded in LULC data.

The preference of the tourism sector for environmentally sensitive areas creates the demand for careful planning ensuring the preservation of the environment and scarce natural resources (Bardolet & Sheldon 2008). Currently, the stakeholders are aware of the importance of resorting to spatial planning as an instrument for ensuring the sustainability of tourism on these islands. In regard to the policy agents, these must applying what is described by some authors as "sustainable development through product-led tourism" (Hunter 1997). Because uncontrolled land development pressure had a tremendous impact on the main islands landscapes, one cannot ignore the specific problems these islands face because of tourism-derived pressure. Tourism comes with economic, social, and environmental costs (Mathieson & Wall 1982). Therefore, its development must be carefully planned. Inherently tourism is an activity that relies on and uses the landscape. Tourism's development on many islands has been marked by significant impacts on the landscape. These impacts call for the need to pay particular attention to the problems of tourism development on the islands (Butler et al. 1993). Spatial planning, a keystone of tourism development, is particularly important for touristic islands. Spatial planning assumes a key role in the preservation of sensitive areas and conservation of landscapes. Nowadays, there is political will and communal awareness of the need for sustainable development on the islands.

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IV. Peer-reviewed articles

IV. Peer-reviewed articles

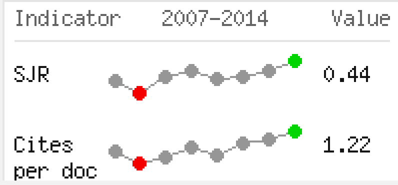
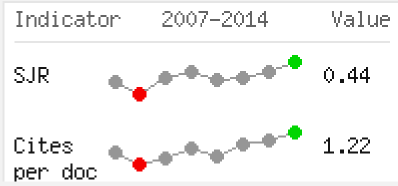
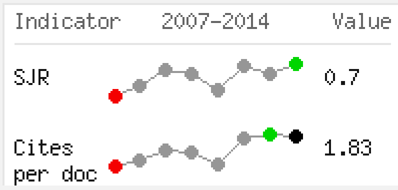
4.1. Background information

The aim of this research is to propose novel methods for quantifying and visualizing geographical information that supports the spatial planning decision-making process when addressing LULC patterns. These methods have been published in peer-reviewed journals. In order to achieve the aim of the research, this thesis presents novel spatially explicit methods for modeling, analyzing, and representing LULC data. Hereafter, the five peer-reviewed articles are presented (Table 10). These five articles are the cornerstone of the thesis. The first of the articles was submitted on October 2014. As of May 2016, three of these articles have been published, one is accepted and available as an advance online publication, and another is under review (Table 11). Each of the articles is specifically oriented towards a specific research question and one of the research objectives. Together the five articles seek to accomplish the research aim (Table 10).

Table 10. The connection between the articles.

Research aim: propose novel methods for quantifying and visualizing geographical information in order to aid the spatial planning decision-making process when addressing LULC patterns.					
	Research questions		**Research objectives**		**Peer-reviewed articles**
#1	What are the contemporary land use patterns and trends on the Macaronesian islands of Portugal and Spain?	→	Propose a novel method for representing and analyzing LULC patterns and trends.	→	Rodrigues, M. (Advance online publication). Land-use in the Macaronesian islands of Portugal and Spain. Journal of Maps.
	↓				
#2	What is the contemporary pattern of coastal land use on the main islands?	→	Propose a novel method for representing and analyzing coastal patterns.	→	Rodrigues, M. (2016). Representing coastal land use in the island of Gran Canaria. Journal of Maps, 12(2), 311–315.
	↓				
#3	What is the contemporary altitudinal pattern of land cover on the main islands?	→	Propose a novel method for representing and analyzing altitudinal patterns.	→	Rodrigues, M. (Manuscript under review). Land cover on the main Macaronesian islands of Portugal and Spain: A graphical method for representing the altitudinal zonation of geospatial data.
	↓				
#4	What is the contemporary pattern of land development pressure on the main islands?	→	Propose a novel method for deducing and representing land development pressure.	→	Rodrigues, M. (2016). GIS-based modeling of a rescaled surface of land development pressure in the Macaronesian islands. GIScience & Remote Sensing, 53(3), 320-336.
	↓				
#5	How strong is the relationship between settlement patterns and the terrain on the main islands?	→	Propose a novel morphological typology for settlement patterns.	→	Rodrigues, M. (2015). A spatial typology for settlement pattern analysis in small islands. GeoFocus, 15, 3-26.

Table 11. The peer-reviewed articles.

	Article title	Journal	Journal Impact Factors	Submitted	Accepted
#1	Land-use in the Macaronesian islands of Portugal and Spain	*Journal of Maps* 	**2015 JOURNAL CITATION REPORTS (JCR)** Journal Impact Factor: 1.193  www.scimagojr.com **Google Scholar Metrics (2010-2014)** h5-index: 12 h5-median: 14	29 May 2015	30 November 2015
#2	Representing coastal land use in the island of Gran Canaria.	*Journal of Maps* 	**2015 JOURNAL CITATION REPORTS (JCR)** Journal Impact Factor: 1.193  www.scimagojr.com **Google Scholar Metrics (2010-2014)** h5-index: 12 h5-median: 14	12 November 2014	30 January 2015
#3	Land cover on the main Macaronesian islands of Portugal and Spain: A graphical method for representing the altitudinal zonation of geospatial data	Under review	Under review	25 January 2016	Under review
#4	GIS-based modeling of a rescaled surface of land development pressure in the Macaronesian islands	*GIScience & Remote Sensing* 	**2015 JOURNAL CITATION REPORTS (JCR)** Journal Impact Factor: 1.770  www.scimagojr.com **Google Scholar Metrics (2010-2014)** h5-index: 15 h5-median: 24	03 June 2015	06 January 2016
#5	A spatial typology for settlement pattern analysis in small islands	*GeoFocus* geofocus	**Google Scholar Metrics (2010-2014)** h5-index: 4 h5-median: 5	26 October 2014	08 January 2015

In spatial terms, the articles increase the complexity of the analysis. The first three articles focus on geovisualization methods and use available CLC data. The first article is general in scope and gives a wider perspective of the study area. The second article shifts the focus to the main islands and increases the complexity of the analysis by focusing on the coastal areas. The third article presents a method that allows displaying the altitudinal zonation of the four main islands and further increases the complexity of the analysis. The last two articles are dedicated to GIS-based modeling and try to contribute some comparable data for this region. As mentioned, on these islands the existing available geospatial data solutions do not conform to the need for European data on different territorial levels on a trans-regional and trans-border perspective. The only comparable LULC data available for all the studied islands are the CLC datasets. However, CLC has a limited scale for more detailed studies. Thus, the fourth article demonstrates a method that rescales CORINE data to a 30 m resolution surface, whereas the fifth and final article, demonstrates the method used for extracting continuous artificial surfaces from high-resolution images and making them into a 5 m resolution surface of settlements. Thus in spatial terms the articles start with a regional scale (i.e. the Macaronesian islands of Portugal and Spain) and proceed all the way to a 5 m resolution data set, which allows mapping the settlements across the four main islands. The contents of each article are now briefly outlined.

#1 Article*: Rodrigues, M. (Advance online publication). Land-use in the Macaronesian islands of Portugal and Spain. Journal of Maps.*

This article made it possible to answer the first research question: "What are the contemporary land use patterns and trends on the Macaronesian islands of Portugal and Spain?". In doing so it fulfilled the first research objective by proposing a novel method for representing and analyzing LULC patterns and trends. Through the published map the aim is to depict the main land use categories and changes, across the Macaronesian islands of Portugal and Spain. The map presents a novel technique for summarizing LULC data into a custom-made 2D static graph-based display. To convey the temporal dimension, the method positions the graphics following a timeline (1990-2006). This custom display provides a framework to study and represent LULC data by overcoming common visual effectiveness issues. The proposed approach is flexible and suitable for application elsewhere by making it possible to draw visual impressions and comparisons in a straightforward manner.

***#2 Article**: Rodrigues, M. (2016). Representing coastal land use in the island of Gran Canaria. Journal of Maps, 12(2), 311–315.*

This article accomplished the second research objective by proposing a novel method for representing and analyzing coastal patterns. The article used the island of Gran Canaria as a study area. Afterwards, the proposed method was employed to answer the second research question: “What is the contemporary pattern of coastal land use on the main islands?”. Through the published map, this article presents a method for summarizing coastal patterns of LULC into arc/sectors of a graph by setting up spatial units of analysis based on compass directions suitable to organize, analyze, and depict spatial data. The method allows the easy detection of patterns and visualization of similarities between two or more sets of coastal LULC data.

***#3 Article**: Rodrigues, M. (Manuscript under review). Land cover on the main Macaronesian islands of Portugal and Spain: A graphical method for representing the altitudinal zonation of geospatial data.*

By representing the altitudinal zonation of the four main Macaronesian islands of Portugal and Spain, this article answers the third research question: “What is the contemporary altitudinal pattern of land cover on the main islands?”. By presenting a novel graphical method for representing and analyzing altitudinal patterns, this article accomplished the third research objective. This article conceptualizes and demonstrates a 2D static graph-based method for representing the altitudinal zonation of geospatial data. The method presented provides a framework to study and represent multivariate spatial data along altitudinal gradients and multiple compass directions. The published map highlights that this novel 2D static graph-based method summarizes vast amounts of information and facilitates the identification of spatial patterns and trends, thus enabling various applications in several fields.

***#4 Article**: Rodrigues, M. (2016). GIS-based modeling of a rescaled surface of land development pressure in the Macaronesian islands. GIScience & Remote Sensing*, 53(3), 320-336.

This article is representative of the fourth research objective: “Propose a novel method for deducing and representing land development pressure.” Using São Miguel, Madeira, Gran Canaria, and Tenerife as study areas, the article directly answers the fourth research question: “What is the contemporary pattern of land development pressure on the main islands?”. This article proposes a method of modeling a spatially explicit representation of land development pressure by resorting to an inverse distance weighting interpolation. Quantifying and identifying the islands' pattern of land development pressure creates a variable that can play an important role in further modeling of anthropogenic spatial processes.

***#5 Article**: Rodrigues, M. (2015). A spatial typology for settlement pattern analysis in small islands. GeoFocus, 15, 3-26.*

This article represents the fifth research question and objective. The article proposed a novel morphological typology for settlement patterns. Once again by using São Miguel, Madeira, Gran Canaria, and Tenerife as study areas, the article directly answers the fifth and final research question: "How strong is the relationship between settlement patterns and the terrain on the main islands?". This research addresses the islands' lack of large-scale spatial data since there are no LULC datasets covering all these islands at a suitable scale for more detailed studies. Due to the large-scale data produced, settlement differentiation is only possible through a morphological approach. Therefore, a morphological, restricted typology is proposed. In order to apply the proposed settlement typology in a systematic and representative analysis, the study concludes with measuring the relationship between settlement types and terrain attributes through a multinomial logit model. Overall, the study contributes to a better understanding of the islands' settlement patterns and uses a method that can be applied elsewhere.

4.2. #1 Article

Rodrigues, M. (Advance online publication). Land-use in the Macaronesian islands of Portugal and Spain. *Journal of Maps*.

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SOCIAL SCIENCE

Land-use in the Macaronesian islands of Portugal and Spain

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ABSTRACT
This article outlines the method used in designing a thematic map of land-use. The aim is to depict the main land-use categories and changes, across the Macaronesian islands of Portugal and Spain, between 1990 and 2006. The map presents a novel technique of summarizing land-use/land-cover (LULC) data into a custom-made 2D static graph-based display. The method proposes depicting the region of interest inside a hollow circle chart, commonly known as 'doughnut chart'. The void inside the chart allows placing a complete cartographic representation, whereas the circle chart itself allows displaying statistical data of the encircled cartographic representation. To convey the temporal dimension, the method positions the graphics following a timeline. This custom display provides a framework to study and represent LULC data, overcoming common visual effectiveness issues. The proposed approach is flexible and suitable for application elsewhere, making it possible to draw visual impressions and comparisons in a straightforward manner.

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1. Introduction

\Although land-use/land-cover (LULC) studies are diverse (Levine & Kaufman, 2008; Nigel, Rughooputh, & Boojhawon, 2015; Vorel & Grill, 2015), there is still a field that can be greatly improved: LULC representation and visualization methods. As researchers have an increasing amount of LULC data, there is a continuous need for tools and methods to synthesize information (Rodrigues, 2016). On this matter, a dominant approach relies in coupling geographic information science (GIS) techniques, with the use of geo-visualization, to accelerate the process of visual geospatial exploration (Gugl, 2009). As an interdisciplinary area, geo-visualization integrates approaches from several scientific fields to provide theory, methods, and tools for visual exploration, analysis, synthesis, and presentation of geospatial data (MacEachren & Kraak, 2001). In addition, research acknowledges that there is a growing need for novel approaches to represent geospatial data in a visual form that can improve pattern recognition and hypothesis generation (Bodum, 2005).

In recent decades, human-induced landscape changes were profound at a global scale (Foley et al., 2005); these changes have also affected the small and isolated Macaronesian islands of Portugal and Spain. Due to the islands' ecological importance (Sundseth, 2009), land-change studies are of particular significance to this region. In fact, despite representing only 0.2% of the EU territory, these islands host over a quarter of EU's most endangered and vulnerable flora (Sundseth, 2009). Therefore, the supplemental Main Map discussed in this article encompasses the 18 inhabited Macaronesian islands of Portugal and Spain. The study aims to analyze and measure, the main land-use categories and changes, between 1990 and 2006. A period marked by a rapid increase in land development, which ended with the 2007–2008 financial crisis. The results, deducing landscape proportions and rates of change, are presented in a single map using the proposed method.

In land-change assessment, change matrices are the main technique used to show changes across a landscape. A change matrix represents transitions among LULC categories, keeping track of area shifts among categories. It is a technique widely applied in land-change research (Fuchs, Herold, Verburg, Clevers, & Eberle, 2015). Nonetheless, when dealing with several study cases, change matrices may turn out too extensive, thus becoming impractical and ineffective. On the other hand, cartographic methods such as choropleth maps (Sun, Kronenfeld, & Wong, 2013), flow maps (Guo, 2009), and cartograms (Li & Clarke, 2012), are the prevailing techniques used to depict geospatial data thematically. Contrary to tabular displays, these methods are spatially explicit, though to varying degrees, and symbols can be combined and overlaid to further enrich the depiction of data. However, a common drawback among cartographic methods occurs when data items overlap in the data-view, making patterns hard to perceive due to occlusion. This drawback is known as the visual effectiveness problem (Guo, Chen, MacEachren, & Liao, 2006). In order to address clutter and over-plotting, several views can be represented alongside the main data-view, a common design strategy, where the geographic

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data-view is presented alongside further data of interest, such as data plots and tables. Alam, Kobourov, and Veeramoni (2015) classify this approach as augmented map visualizations.

In addition, besides tabular and cartographic representations, LULC data may also be presented in standard static displays, such as graphs and charts. Despite being non-spatially explicit, these methods are well-fitted to display multivariate data. For this reason, the supplemental Main Map discussed in the present article showcases the coupling of cartographic representations and charts, adapting circle and bar charts to aid the representation of LULC data.

The main goal of the supplemental Main Map discussed in this article, is to propose a method of representing multivariate LULC data, in a meaningful and concise manner. First, a GIS-based spatial analysis was employed, deducing statistical data of land-use categories across eighteen islands. Second, the results are visualized in a custom-made 2D static graph-based display. Overall, this article provides an original contribution to the ongoing debate about land-change and LULC dynamics, by means of the development of a novel method of analyzing and representing LULC data. The remainder of this article is organized as follows. The next section presents the study area and data sources. Section 3 presents the map design, whereas Section 4 concludes the article.

2. Study area and data

Macaronesia is a bio-geographical region comprising several archipelagos in the Atlantic Ocean, extending outwards from the coast of Europe and Africa (Fernández-Palacios et al., 2011). The archipelagos belong to three countries: Portugal, Spain, and Cape Verde. The supplemental Main Map discussed in the present article encompasses three archipelagos: Azores, Madeira, and the Canary Islands. The Azores and Madeira belong to Portugal, whereas the Canaries belong to Spain. Climatically, the Macaronesian islands of Portugal and Spain span a transition zone between temperate and subtropical climate. However, a rugged and volcanic orography originates a diversity of microclimates and landscapes, ranging from arid environments to humid evergreen forests.

The most important ecosystem in the Macaronesia bio-geographical region is the Atlantic laurel forest, which develops in the archipelagos' areas with very low seasonal temperature variation and high precipitation. The ecological importance of the laurel forest relies in the fact that its vegetation is composed of the remnants of Palaeotropical geoflora (Fernández-Palacios et al., 2011), a flora that thrived in the Paleogene Period (c. 64–25 Ma) after the Cretaceous-Paleogene extinction event. Having been wiped out from the mainland, because of the Quaternary glaciation, Europe's last impoverished remnants of Palaeotropical geoflora survived in these archipelagos, subsisting where the impact of the Quaternary climate change was moderated by the oceanic influence (Fernández-Palacios et al., 2011).

The data used for this map is available from public domain sources. CORINE land-cover (CLC) data sets were the map's primary data source. CLC are geospatial datasets of the European landscape deduced from remote sensing. These public domain data sets (www.eea.europa.eu/data-and-maps) provide an inventory of LULC categories organized hierarchically in three levels as a comparable cartographic product. CLC level1 corresponds to the main categories of land-use (artificial, agricultural, forests and semi natural, wetlands, water bodies), CLC level2 covers land-cover entities at a higher level of detail (i.e. 15 categories), whereas the disaggregated CLC level3 is composed of 44 land-cover categories. Therefore, the aggregated CLC level1 allows characterizing land-use, whilst from CLC level2 onward the CLC data sets characterize land-cover. The availability of comparable data sets using similar source data and having the same technical characteristics (e.g. 25 ha minimum mapping unit), allows a quantitative characterization and assessment of land-change, over a period of two decades. The first iteration of CLC data covered the reference year of 1990 with subsequent releases covering the years 2000 and 2006. The latest 2012 update is still under production. Finally, in order to depict bathymetry, the map uses 'Natural Earth' data, another public domain map data source (www.naturalearthdata.com).

3. Map design

A GIS-based analysis was performed to determine changes in the areal extent of land-use categories by comparing land-use data from two points in time: 1990 and 2006. Through this approach, the goal was to measure the islands' main land-use categories and change, based on two years of CLC level1 data. This analysis allowed establishing the difference of land-use areas, to deduce the arithmetic calculation of change in total land area, and the rates of change across CLC level1 categories. In these islands, CLC level1 is represented by three land-use categories (artificial; agricultural; forest and semi natural), whereas due to the 25 ha minimum mapping unit, the remaining CLC level1 categories are absent (i.e. wetlands; water bodies).

In order to frame a discussion about land-use, map design was one of the most challenging task in the study. There was the need to display eighteen islands in a single map. Nonetheless, a balanced map design was achieved, and visual relationships were designed to achieve appropriate visual hierarchy and optimize visual contrast. Due to the approach followed, the supplemental Main Map discussed in the present

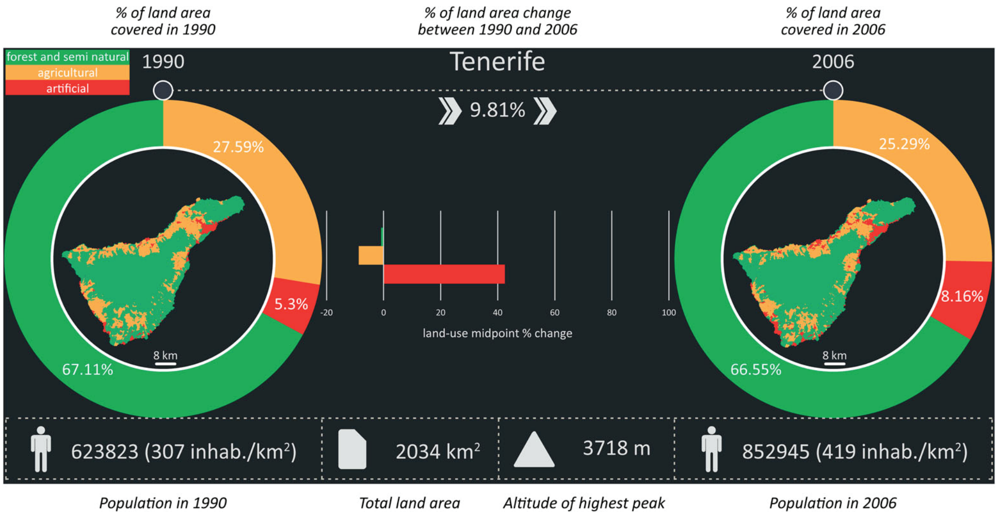

Figure 1. Example of the custom-made 2D static graph-based display.

article can be categorized as an augmented map visualization (Alam et al., 2015), because several data-views are simultaneously represented to depict the eighteen inhabited Macaronesian islands of Portugal and Spain.

Because the map was intended to individually depict eighteen islands, it has an ISO standard A0 (841×1189 mm) page format. As for color, the map uses the CMYK color model. Nonetheless, color is used sparsely, as the map only illustrates three land-use categories. For the typography, the map uses the Calibre font in sizes ranging from 6 to 50 pt.

The map's novel approach is the custom-made 2D static graph-based display. As shown in Figure 1, this approach allows representing each island and its associated data individually. The region of interest is depicted inside a hollow circle chart, commonly known as 'doughnut chart'. Thus, the void inside the chart allows placing a complete cartographic representation, whereas the circle chart itself allows displaying statistical data of the encircled cartographic representation (Figure 1).

In order to convey the temporal dimension, Figure 1 positions the graphics following a timeline. In this study, the first year under analysis is 1990, whereas 2006 ends the timeline. Although in the supplemental Main Map discussed in the present article, only two years are depicted, the method allows placing more years as needed. This design follows the multiple-static-maps strategy (Monmonier, 1990), which juxtaposes graphics for a simultaneous visual comparison of time units. The multiple-static-maps strategy suits particularly well LULC assessments, because each graphic presents a snapshot for a discrete period. Thus, if two or more graphics are juxtaposed, the reader can visually compare LULC data (Rodrigues, 2016). As shown in Figure 1, this method allows inferring trends over time, including LULC gains and losses.

The positioning of a bar chart between the circle charts allows further depicting data. In the case of this study, the bar chart illustrates the land-use midpoint percentage change between 1990 and 2006. Moreover, the lower-most section of Figure 1 allows enriching the data-view with contextual information, in the case of this study, demographic statistics for each year under analysis, total land area, and the altitude of the highest peak. Overall, the proposed method was devised with a graphical hierarchy that makes it intuitively easy for the reader to discover the key concepts and relationships of the data portrayed.

3.1. Software

Spatial analysis and data manipulation were accomplished with ArcGIS® Desktop 10, and map layouts exported to the Illustrator® file format. Land-use statistical analysis was performed with Excel® 2013. Finally, map composition, charting, and labeling were all made with Illustrator® CS6.

4. Conclusion

This article presented a map using a novel method of analyzing and representing LULC data in a meaningful and concise manner. By presenting a technique summarizing LULC data into a graph-based display, this method can simplify complex LULC data in a single data-view. As shown in the supplemental Main Map, the method can be used to: (1) depict the overall LULC patterns; (2) facilitate visual comparisons among study areas and/or time-series; and (3) facilitate the identification of LULC gains, losses, and trends. Ultimately, the method makes it possible to easily draw visual impressions of LULC data, establishing the difference of land-use areas in order to deduce landscape proportions and rates of change.

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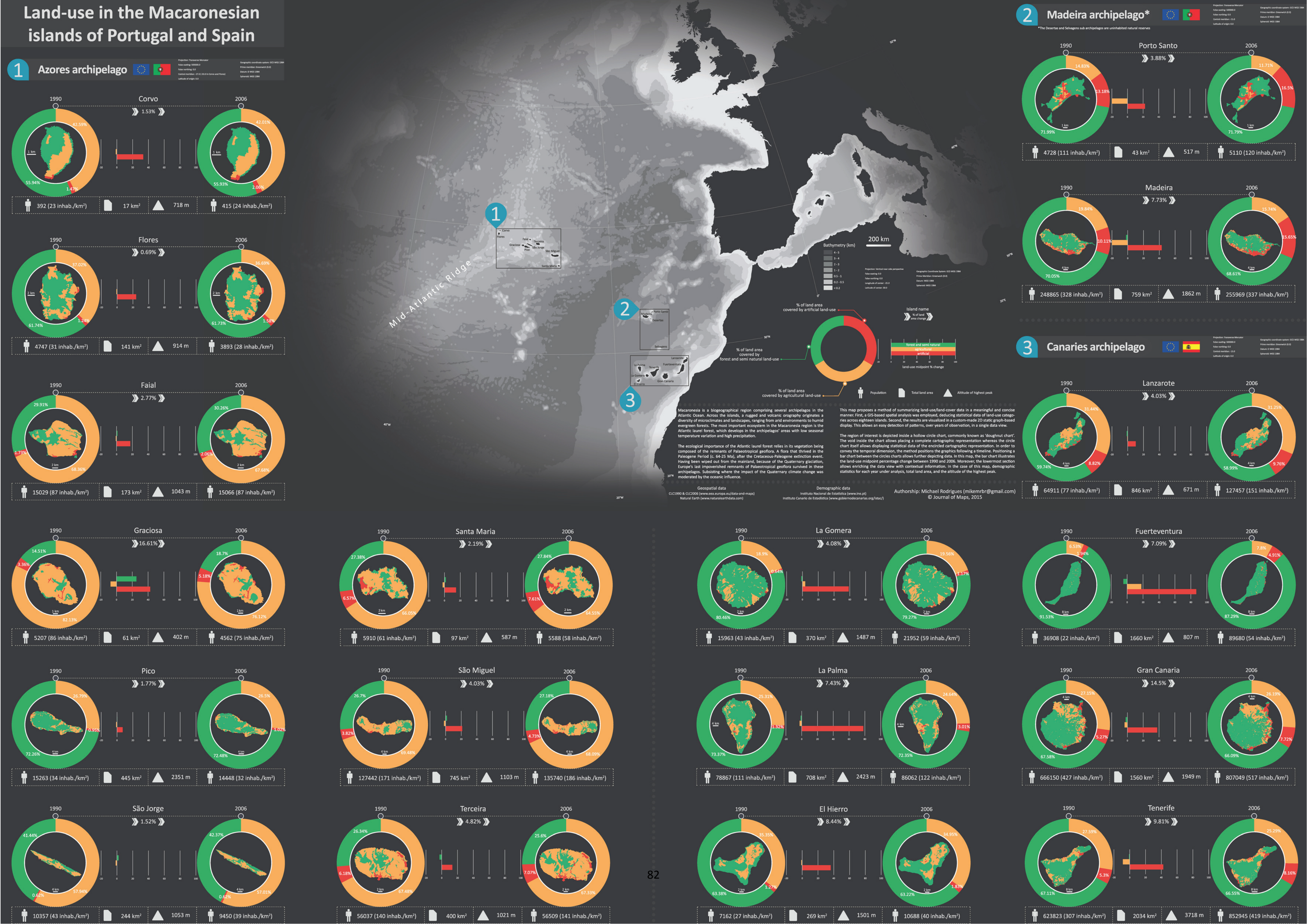

Land-use in the Macaronesian islands of Portugal and Spain
1 Azores archipelago
Corvo
1990
2006
1.53%
392 (23 inhab./km²)
17 km²
718 m
415 (24 inhab./km²)
Flores
0.69%
4747 (31 inhab./km²)
141 km²
914 m
3893 (28 inhab./km²)
Faial
2.77%
15029 (87 inhab./km²)
173 km²
1043 m
15066 (87 inhab./km²)
Graciosa
16.61%
5207 (86 inhab./km²)
61 km²
402 m
4562 (75 inhab./km²)
Pico
1.77%
15263 (34 inhab./km²)
445 km²
2351 m
14448 (32 inhab./km²)
São Jorge
1.52%
10357 (43 inhab./km²)
244 km²
1053 m
9450 (39 inhab./km²)
Santa Maria
2.19%
5910 (61 inhab./km²)
97 km²
587 m
5588 (58 inhab./km²)
São Miguel
4.03%
127442 (171 inhab./km²)
745 km²
1103 m
135740 (186 inhab./km²)
Terceira
4.82%
56037 (140 inhab./km²)
400 km²
1021 m
56509 (141 inhab./km²)
2 Madeira archipelago*
*The Desertas and Selvagens sub archipelagos are uninhabited natural reserves
Porto Santo
3.88%
4728 (111 inhab./km²)
43 km²
517 m
5110 (120 inhab./km²)
Madeira
7.73%
248865 (328 inhab./km²)
759 km²
1862 m
255969 (337 inhab./km²)
3 Canaries archipelago
Lanzarote
4.03%
64911 (77 inhab./km²)
846 km²
671 m
127457 (151 inhab./km²)
Fuerteventura
7.09%
36908 (22 inhab./km²)
1660 km²
807 m
89680 (54 inhab./km²)
Gran Canaria
14.5%
666150 (427 inhab./km²)
1560 km²
1949 m
807049 (517 inhab./km²)
Tenerife
9.81%
623823 (307 inhab./km²)
2034 km²
3718 m
852945 (419 inhab./km²)
La Gomera
4.08%
15963 (43 inhab./km²)
370 km²
1487 m
21952 (59 inhab./km²)
La Palma
7.43%
78867 (111 inhab./km²)
708 km²
2423 m
86062 (122 inhab./km²)
El Hierro
8.44%
7162 (27 inhab./km²)
269 km²
1501 m
10688 (40 inhab./km²)
Mid-Atlantic Ridge
200 km
Bathymetry (km)
% of land area covered by artificial land-use
% of land area covered by forest and semi natural land-use
% of land area covered by agricultural land-use
Island name
% of land area change
forest and semi natural
agricultural
artificial
land-use midpoint % change
Population
Total land area
Altitude of highest peak
Macaronesia is a biogeographical region comprising several archipelagos in the Atlantic Ocean. Across the islands, a rugged and volcanic orography originates a diversity of microclimates and landscapes, ranging from arid environments to humid evergreen forests. The most important ecosystem in the Macaronesia region is the Atlantic laurel forest, which develops in the archipelagos' areas with low seasonal temperature variation and high precipitation.
The ecological importance of the Atlantic laurel forest relies in its vegetation being composed of the remnants of Palaeotropical geoflora. A flora that thrived in the Paleogene Period (c. 64-25 Ma), after the Cretaceous-Paleogene extinction event. Having been wiped out from the mainland, because of the Quaternary glaciation, Europe's last impoverished remnants of Palaeotropical geoflora survived in these archipelagos. Subsisting where the impact of the Quaternary climate change was moderated by the oceanic influence.
This map proposes a method of summarizing land-use/land-cover data in a meaningful and concise manner. First, a GIS-based spatial analysis was employed, deducing statistical data of land-use categories across eighteen islands. Second, the results are visualized in a custom-made 2D static graph-based display. This allows an easy detection of patterns, over years of observation, in a single data view.
The region of interest is depicted inside a hollow circle chart, commonly known as 'doughnut chart'. The void inside the chart allows placing a complete cartographic representation whereas the circle chart itself allows displaying statistical data of the encircled cartographic representation. In order to convey the temporal dimension, the method positions the graphics following a timeline. Positioning a bar chart between the circles charts allows further depicting data. In this map, the bar chart illustrates the land-use midpoint percentage change between 1990 and 2006. Moreover, the lowermost section allows enriching the data view with contextual information. In the case of this map, demographic statistics for each year under analysis, total land area, and the altitude of the highest peak.
Geospatial data
CLC1990 & CLC2006 (www.eea.europa.eu/data-and-maps)
Natural Earth (www.naturalearthdata.com)
Demographic data
Instituto Nacional de Estatística (www.ine.pt)
Instituto Canario de Estadística (www.gobiernodecanarias.org/istac/)
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4.3. #2 Article

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SCIENCE

Representing coastal land use in the island of Gran Canaria

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This map displays a geographic information system-based spatial analysis representing coastal land use in the island of Gran Canaria. It presents a method of summarizing coastal patterns of land use/cover into arc/sectors of a graph, setting up spatial units of analysis based on compass directions suitable to organize, analyse and depict spatial data. The method allows the easy detection of patterns and visualization of similarities between two or more sets of coastal land use/cover data. This paper outlines the methods used in designing the map.

Keywords: coastal areas; land use; spatial analysis; geographic visualization

1. Introduction

In Europe, coastal management is a key topic in planning, with the European Commission operating a programme on ‘Integrated Coastal Zone Management’ (ICZM) from the mid-1990s. ICZM attempts to ‘balance the needs of development with protection of the very resources that sustain coastal economies’ (EEA, 2006, p. 7). The role and significance of coastal areas are well documented in several studies (Roth, Oke, & Emery, 1989; Small & Nicholls, 2003; Thom, Williams, & Diefenderfer, 2005), with the importance magnified in the case of small islands, such as Gran Canaria, where tourism development and associated commercial and residential growth have dramatically changed the coastal landscape.

Gran Canaria is the second most populous of the Canary Islands, with an area of 1560 km^2 and approximately 850,000 inhabitants. Some of Gran Canaria’s coastal areas are highly impervious and urbanization rates along the coast are much higher than further inland. In recent decades, the coastal strip has experienced a rapid transformation, mainly due to tourist development. The impact of this transformation has been recorded in land-use/land-cover (LULC) data.

Although studies examining land change are diverse (Mas, 1999; Munsi, Malaviya, Oinam, & Joshi, 2010; Schulz, Cayuela, Echeverria, Salas, & Rey Benayas, 2010; Yuan, Sawaya, Loeffelholz, & Bauer, 2005), LULC representation and visualization methods can be greatly improved. As researchers have increasingly large amounts of LULC data, there is a continuous need for tools and methods to synthesize information.

The main goal of this Main Map is to propose a method to represent coastal LULC in islands, in a meaningful and concise manner. Using CORINE datasets as data sources, geographic

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information system-based spatial analysis was employed to represent the distribution of land use relative to a 5-km coastal buffer zone. The results of the analysis are visualized in the form of a diagram, summarizing coastal patterns of LULC into arc/sectors of a graph, setting up spatial units of analysis based on compass directions suitable to organize, analyse and depict spatial data. The map is capable of showing coastal land-use data, whilst depicting Gran Canaria's overall land-use pattern, thus allowing the easy detection of patterns over different years of observation.

2. Concepts and framework

Within the field of land change assessment, a key aspect of all studies is data presentation. In land change assessment, change matrices are a dominant tabular method to highlight LULC changes. These matrices keep track of LULC shifts from one category to other categories, and are widely applied in land change research (Xu, Liao, Shen, Zhang, & Mei, 2007). Nonetheless, for large areas or several study cases, they may turn out too extensive, thus becoming impractical and ineffective. Besides tabular form, LULC data may also be presented in graphical forms, such as maps, graphs and diagrams.

Once several LULC data sources become available for an area, LULC data might be treated as spatiotemporal data, which implies specific visualization methods. Several studies have covered visualization methods of spatiotemporal data (Andrienko, Dykes, Fabrikant, & Wachowicz, 2008; Claramunt, Jiang, & Bargiela, 2000; Monmonier, 1990; Peuquet, 1994). These graphical methods make it possible to easily draw visual impressions of spatiotemporal data, facilitate comparisons and present characteristics in a straightforward manner. Monmonier (1990) highlights several graphical methods to portray quantitative spatiotemporal data. Two of the main methods addressed are the 'single-static-map' (p. 30) and 'multiple-static-maps' (p. 30) strategies. 'Single-static-map' strategies incorporate the temporal dimension through techniques ranging from 'complex point symbols, or temporal glyphs, to generalized trend-surface or flow-linkage maps' (Monmonier, 1990, p. 30). The 'multiple-static-maps' strategy 'juxtaposes two or more maps for a simultaneous visual comparison of time units' (Monmonier, 1990, p. 30). The 'multiple-static-maps' strategy suits LULC change assessment particularly well, since each map presents a snapshot for a discrete period of time. Thus, if two or more maps are juxtaposed, the user can visually compare LULC patterns. This may be sufficient for most studies; nonetheless, issues arise once it becomes difficult to represent LULC data analysis, such as gains, losses and net change. The solution resides in resorting to other graphical representations. However, a major problem with graphical representations of geographic data lies in the need to display 'both the attribute space familiar to the statistician and the geographic space that provides the necessary sense of place and relative location' (Monmonier, 1990, p. 38).

In order to represent attribute and geographic space, the current map proposes an adaptation of rose diagrams to represent LULC data. Rose diagrams are circular histograms in which the frequency of vector data in predefined azimuthal classes is plotted as sectors of circles with a common origin (Baas, 2000). Early applications of rose diagrams can be found in Curray (1956) where the rose diagram is used to show direction as well as magnitude. Over the years, the method has become widely used in the Earth sciences (Baas, 2000). Rose diagrams are common ways of visualizing geographic data, and extensively used in several studies. Examples include the analysis of spatial patterns of vegetation fire (Brivio, Grégoire, Koffi, & Ober, 1997), terrain pattern recognition (Miliaresis, 2008) and spatial orientation of urban expansion (Xu et al., 2007). Since LULC data are not directional per se, it needs to be analysed through appropriate methods in order to be represented with rose diagrams. In order to do this, Xu et al. (2007) employed 'concentric circle and sector analysis methods' (p. 20). According to the authors, the 'concentric circle method' is 'effective for analysing the quantity and distribution of different categories of land use with respect to distance from a pre-determined urban center' (Xu et al., 2007, p. 20). On the other hand, 'sector analysis' can transpose the cardinal directions to a circular graph. With these methods, Xu et al. (2007) utilized graphs to illustrate the spatial orientation of urban expansion. The authors named these graphs 'rose diagrams of urban expansion' (p. 23). So far, however, there has been little discussion about alternative methods to represent LULC data. This Main Map proposes an enhancement of existing methods in order to present a diagram for evaluations of coastal LULC gains and losses.

3. Methods

Gran Canaria's CORINE 1990 and 2006 datasets provided the map's data sources. CORINE datasets (http://www.eea.europa.eu/data-and-maps) are part of the programme started in 1985 by the European Community to generate digital land-cover maps covering Europe. The availability of comparable datasets using similar source data and having the same technical characteristics (1:100,000 scale and 25 ha minimum mapping unit) allows a quantitative characterization and assessment of land change, over a period of two decades. The first iteration of the CORINE data covered the reference year of 1990 with subsequent releases covering the years 2000 and 2006. The latest 2012 update is still under production.

The map consists of four figures. The two top figures depict Gran Canaria's overall land use in the two years under analysis, whilst the bottom two figures shows a coastal land-use diagram for each year. Empirical knowledge of the island's landscape has established the importance of working with compass directions, since the trade winds carry moisture to the northeast of the island making this area cooler, wetter and more favourable to agriculture, which has been the island's economic driving force up to the mid-twentieth century. As such, the North-northeast (NNE) and East-northeast (ENE) sectors have become more populated and with stronger urban dynamics, and this has been recorded in the LULC data.

In order to process the data, and with the origin in the island's centroid, the island was divided into eight regions. These eight regions are meant to represent the cardinal and intermediate directions, thus dividing the island into eight geographic sectors. The coastline identified in the CORINE dataset was then extracted and buffered in 1 km increments, up to 5 km, thus creating five buffers. These buffers were then intersected with the CORINE data set polygons for 1990 and 2006. Finally, these five buffers, filled with land-use data, were intersected with the eight regions representing the island's cardinal and intermediate directions. The final result of this process is, for each of the eight regions, five coastal buffers filled with land-use data for 1990 and 2006. The objective of this procedure was to compute the percentages of land-use classes in each of the intersected buffers within the eight regions.

LULC data are not directional; nonetheless, the proposed diagram with eight sectors and five concentric rings transposes LULC data to geographic units that can serve as basis for further analysis, since it sets up spatial units of analysis based on compass directions suitable to organize, analyse and depict spatial data. The relationship between land use/cover and prevailing winds (trade winds) is clear in many tropical and subtropical islands (e.g. in the Caribbean islands with landscape difference between Windward and Leeward, and in the Atlantic subtropical islands with a North/South difference) and explains why it is important to use rose diagram-like displays to analyse spatial data in these islands.

3.1. *Map design*

The coastal land-use diagram was built by bisecting the angles of a circle by 45°. The eight radial dividers provide the orientation of the cardinal directions and the intermediate directions. In this map, five 1-km buffers have been created. Therefore, the circle was further divided into six concentric rings. The sixth and last interior ring is void of data. The result of this process is a circle, divided by six concentric dividers and eight radial dividers. Thus, the concentric dividers represent the buffers, whilst the radial dividers represent the cardinal and intermediate directions, and divide the circle into the same eight regions (geographic units) that the island had been divided. One of the method's drawbacks is that in the case of an elongate island, oriented in a cardinal direction, some sectors would contain much more area than others, thus the importance of normalizing LULC data as a percentage.

Taking into account the percentage that each class occupies on each buffer in each sector, the concentric and radial dividers can be used to represent the computed data. As with a histogram, the diagram areas should be proportional to the frequency of the data. Since a concentric divider (buffer) in each radial divider takes 45°, 45° represents 100% of the occupation. Taking this into account, we can compute the degrees for each land-use class. For example,

$$\text{artificial} = \left(\text{percentage of artificial area}^{*}45\right)/100.$$

This calculates how many degrees a LULC class needs to bisect the radial divider. Now, in order to represent the data, we need to take into account the angular difference in each radial divider. Starting from 0°, to represent data in the first radial divider (NNE) ending at 45°, 45° would show that a single class occupies 100% of the land use in that buffer and in the NNE sector. Since we want to calculate the degrees that a single class requires to be represented in this first sector, we subtract the value for (1) from the upper boundary value. This is performed iteratively for each class. Therefore, the proposed diagram allows representation of LULC data in both attribute and geographic space. Land-use percentages make the attribute space, whereas the diagram's eight sectors and five concentric rings represent the island's geographic space.

The map design follows the 'multiple-static-maps strategy' (Monmonier, 1990, p. 30), which juxtaposes graphics for a simultaneous visual comparison of time units. In this map, graphics are juxtaposed for 1990 and 2006. As can be seen in the map, this method allows the reader to infer trends over time, including coastal land-use gains and losses. Since the map was intended to be viewed only in printed form, it has an ISO standard A4 page format. Visual relationships were designed to achieve appropriate visual hierarchy and optimize visual contrast. Given that the map depicts only three classes, a decision was made to avoid colour use and design the map in greyscale to increase legibility whilst improving the portrayal of variation in the data. Geographic labelling was hand-made to allow final manual tidying of the text. For the typography, the map uses the Calibre font in sizes ranging from 5 to 13 pt.

4. Conclusions

Graphical representation of LULC provides valuable information for planners and land resource managers. Overall, the map's method can be used to (1) easily draw visual impressions of coastal LULC data; (2) facilitate comparisons among study areas and (3) uncover underlying trends of land change. By presenting a form of summarizing coastal patterns of LULC into arc/sectors of a graph, this method can simplify complex spatial data in a single graphical presentation within a geographic context, which otherwise would occupy extensive tables of data. By setting up geographic units based on compass directions, the method uses spatial units of analysis without resorting to administrative units. And since this method may be easily customized to fit other study areas elsewhere, it can incorporate its graphical dimension into broader approaches contributing to the systematic and representative analysis of LULC.

Software

Spatial analysis and data manipulation were accomplished using Esri ArcGIS 10, with map layouts exported to the Illustrator file format. Land-use statistical analysis was performed using Microsoft Excel 2007. Finally, coastal land-use diagrams, map composition and labelling were made using Adobe Illustrator CS6.

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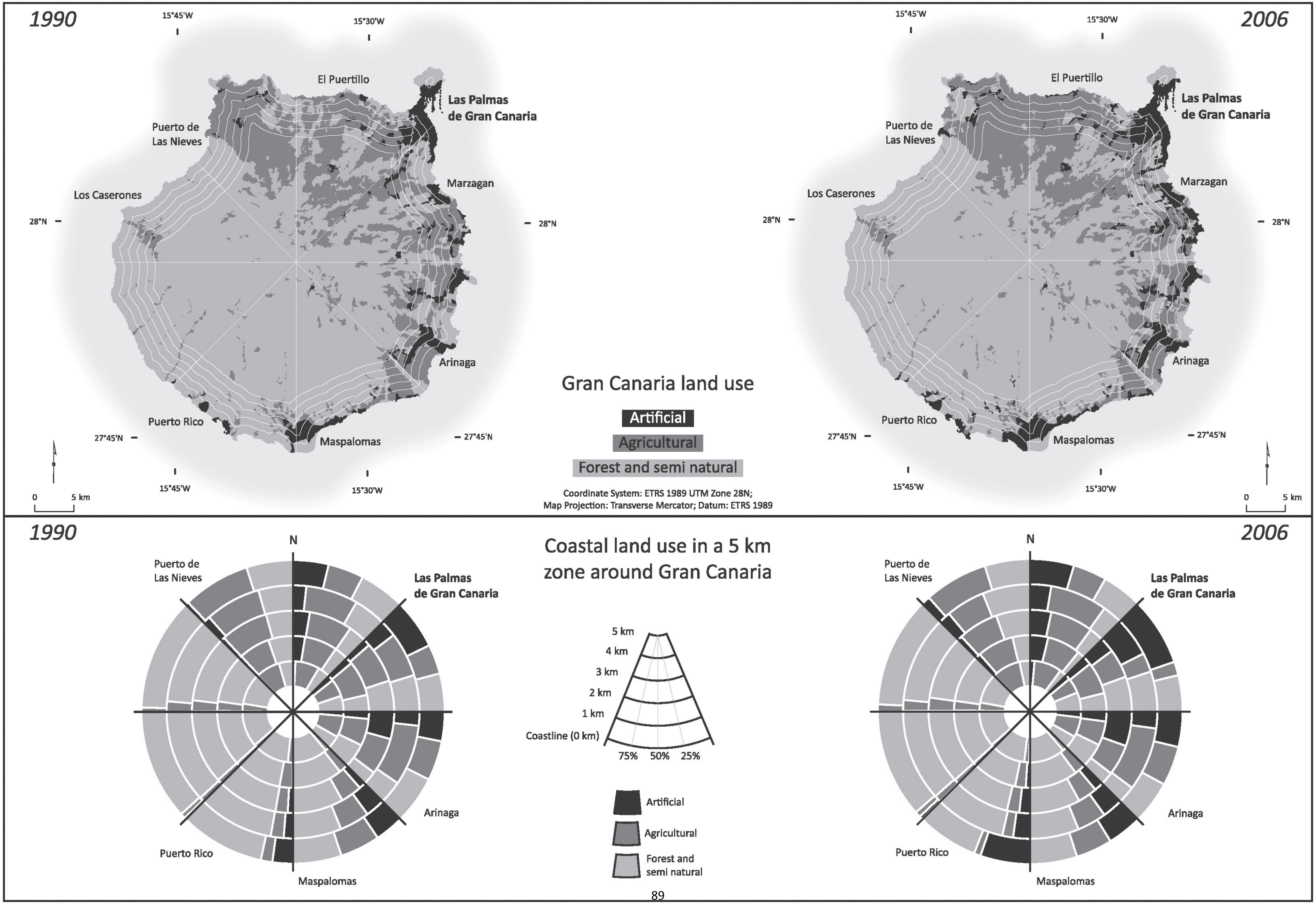

Data source: 1990 & 2006 CORINE datasets (European Environment Agency)

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4.4. #3 Article

Rodrigues, M. (manuscript under review). Land cover on the main Macaronesian islands of Portugal and Spain: A graphical method for representing the altitudinal zonation of geospatial data.

Land cover on the main Macaronesian islands of Portugal and Spain: A graphical method for representing the altitudinal zonation of geospatial data

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This article conceptualizes and demonstrates a 2D static graph-based method for representing the altitudinal zonation of geospatial data. The method presented hereafter provides a framework to study and represent multivariate spatial data along altitudinal gradients and multiple compass directions. To test the effectiveness of the method, the supplemental map graphically represents the altitudinal zonation of three variables: land cover, slope, and aspect on the main Macaronesian islands of Portugal and Spain. The method relies on a spatial analysis, and displays a graphical representation of the information in a custom-made chart named Altitudinal Zonation Radial Chart. The method is flexible, spatially explicit, and meaningful, suitable to be applied elsewhere. The supplemental map highlights that this novel 2D static graph-based method summarizes vast amounts of information, and facilitates the identification of spatial patterns and trends, thus enabling various applications in several fields.

Keywords: land cover; geospatial data; geovisualization; altitudinal zonation; Macaronesia.

1. Introduction

Altitudinal zonation comprises the sorting of data according to elevation (Fernández-Palacios & Nicolás, 1995). To study the vertical organization of landscapes, altitudinal zonation provides valuable information for scientists and planners, through the explicit and implicit relationships between geospatial data and altitude. Although studies examining the altitudinal zonation of geospatial data cover different research fields (Thorpe & Brown, 1989; Oromí et al., 1991; Wondie et al., 2012), far too little attention has been paid to its geographic visualization. Therefore, gaps still exist, and the graphical representation of altitudinal zonation is a topic that can be improved.

A major drawback with extant cartographic methods arises from legibility issues when displaying high-dimensional geospatial data in a single data view (Nöllenburg, 2007). Moreover, whenever it is convenient to present the results in a spatial explicit display, this cannot be conveniently done resorting to other extant methods such as tables. Therefore, to overcome the main drawbacks of extant methods, this article introduces a novel 2D static graph-based method, named Altitudinal Zonation Radial Chart (AZRC).

The AZRC is a novel visualization technique designed to create a geographic representation of the altitudinal zonation of geospatial data in a single static 2D data view. Geovisualization methods range from static 2D to interactive 3D applications, and in contrast to information visualization displaying any abstract data, "geovisualization deals specifically with geospatial data" (Nöllenburg, 2007, p. 264). MacEachren and Ganter's (1990) cognitive approach to geovisualization focus on the explorative side, to gain new scientific insight through images instead of words. Building upon the cognitive approach to geovisualization, several alternative portrayals of geospatial data have been presented (Battersby et al., 2011; Hennemann, 2013; Hennig, 2014; Janicki et al., 2014; Ullah & Kraak, 2015). In this regard, research acknowledges that there is a growing need for novel approaches to represent geospatial data in a visual form that can improve pattern recognition and hypothesis generation (Bodum, 2005). Overall, the method presented herein was devised to contribute to the discussion of alternative visualization methods of geospatial data, and more particularly, to propose a novel technique for representing the altitudinal zonation across several compass directions in a single, static 2D data view.

2. Related work

Cartographic methods such as choropleth maps (Sun, Kronenfeld, & Wong, 2013), flow maps (Guo, 2009), chorems (Reimer, 2010) and cartograms (Li, & Clarke, 2012) are the dominant approach for representing geospatial data in a static 2D data view. These methods are spatial explicit, though to varying degrees, and symbols can be combined and overlaid to further enrich the depiction of data. However, a geospatial data set with several variables (i.e., multivariate) is difficult to visualize in a single 2D static data view. To address clutter and overplotting, several views can be represented alongside the main data view. A common design strategy, where the geographic data view is presented alongside further data of interest, such as data plots and tables. A less straightforward approach uses multivariate data representation that depicts each variable independently and then integrates all variable depictions directly onto a cartographic space, using glyph-based or icon-based techniques (Battersby et al., 2011; Palmucci, Rusi, & Tatangelo, 2016).

To balance the need to display multivariate data with spatial explicit representations, some authors proposed transposing the geographic space into a spatial explicit geometric structure. One early example is the "space-time cube" (Hägerstraand, 1970), where attribute and geographic space can be represented by three dimensions. Recent examples of spatial explicit geometric structure methods include "OD maps" (Wood, Dykes, & Slingsby, 2010), where geographic space is projected into a regular coarse grid nested at two levels. "Grid maps" (Eppstein et al., 2013), a single-level spatially ordered treemap in which all grid cell areas have the same size, orientation and are aligned in a regular grid where the geographic space is projected. "Table cartograms" (Evans et al., 2013), where the grid cell areas match pre-determined areas and "necklace maps" (Speckmann & Verbeek, 2010), where the regions of the underlying two-dimensional map are projected onto intervals on a one-dimensional curve that surrounds the map regions.

A crucial feature of every study addressing altitudinal zonation is data presentation. Altitudinal zonation has been graphically represented in several distinct ways that can be classified into four extant methods. (1) Tables (Martin, Fahey, & Sherman, 2011, p. 535; Wondie et al., 2012, p. 39). (2) Charts (Arteaga et al., 2009, p. 1079; Haider et al., 2010, p. 4005). (3) Cross-sections (Thorpe & Brown, 1989, p. 307; Martin et al., 2011, p. 539). (4) And maps (Thorpe & Brown, 1989, p. 305; Gallardo-Cruz, Pérez-García, & Meave, 2009, p. 475).

The swiftest method of depicting altitudinal zonation is through tables, with columns or rows representing altitudinal belts. Nonetheless, a well-known drawback in every study portraying tabular data is the presentation of a large information structure. Occasionally, there is too much data to be presented in a single table fitting in a reasonable extent, without deriving latent variables through linear and nonlinear dimensionality reduction techniques. Moreover, tables are non-spatial explicit, therefore they cannot visually convey geographic space.

A common drawback to other extant methods (i.e., charts and cross-sections) is that, unlike cartographic approaches (i.e., maps); these methods have a limited geographical extent. As a result, the geographic boundaries for displaying data within the graphical representation are limited. In a study depicting multiple compass directions, the entire study area cannot be accommodated all at once in the display area of a single data view. This issue arises due to the geographical extent required to represent the multiple compass directions of the data.

Finally, cartographic approaches (i.e., maps), albeit being the most spatially explicit method for representing altitudinal zonation, have the drawback of relying in contours to display the altitude onto which the variable(s) of interest is/are plotted at their corresponding coordinates. To maintain legibility, this has the shortcoming of constraining data representation to a very small number of variables. Compound glyph-based techniques can be placed on a map to represent the values of multidimensional attributes (Nöllenburg, 2007). Nonetheless, “if the number of symbols or attributes exceeds a certain limit the symbols become hard to compare” (Nöllenburg, 2007, p. 263).

The fields of geovisualization and information design provide methods to present all the information in a data structure in one single static image. These methods typically encompass the presentation of information in primarily graphical or pictorial form. The use of computerized techniques in geographical research, coupled with the theoretical foundations to visualization set by Bertin ([1967] 2010), and Tufte’s ([1983] 2001) framework of information design, opened new possibilities for accurate static representations of geospatial data. Hence, the same theoretical background and best practices of geovisualization and information design methods (Bertin, [1967] 2010; Tufte, [1983] 2001; Cleveland, 1993) can be applied to altitudinal zonation. However, the graphical representation of altitudinal zonation implies specific methods, to keep a meaningful and spatially explicit representation of geospatial data. A critical issue with graphical representations of geospatial data relies in the need to display “both the attribute space familiar to the statistician and the geographic space that provides the necessary sense of place and relative location” (Monmonier, 1990, p. 38).

Therefore, this article proposes a novel 2D static graph-based method for representing altitudinal zonation, where geospatial data is replaced by an indirect, graphical display of that data, summarizing the information in 360 degrees. This allows a simultaneous representation of multivariate data along several compass directions, in a single data view, hence avoiding the weakness of extant methods. In order to display both attribute and geographic space, and following earlier work (Rodrigues, 2016), the current method proposes spatial units of analysis based on compass directions. In Rodrigues’ method (2016), a coastal zonation chart was proposed as an alternative representation of land-use/land-cover (LULC). These two methods are related, because they set up spatial units of analysis based on compass directions suitable to organize, analyze, and depict geospatial data. However, the present work differs from Rodrigues' (2016) method in three critical points: 1) the coastal zonation chart is a method of summarizing horizontal patterns of LULC data into arc/sectors of a circular graph, whereas, the proposed AZRC is tailored to represent the altitudinal (i.e., vertical) zonation of high-dimensional geospatial data. 2) In the coastal zonation chart, geographic space is organized through multiple concentric GIS-based buffers, whereas the AZRC presents geographic space as naturally occurring altitudinal intervals. 3) Contrary to the coastal zonation chart, which was proposed as an alternative display of LULC data, the AZRC allows representing multivariate data in a single data view, because it adapts the same principles of radar charts. This allows the AZRC to have a more comprehensive attribute space, capable of displaying a wider range of variables. A radar chart is a well-proven geometric technique of plotting multivariate data as a 2D chart where data are displayed along *n* radial axes. These *n* radial axes are integrated into a single radial figure onto which multivariate data can be presented simultaneously. Radar charts have been used as a method for representing geospatial data (Dang, Shi, & Mao, 2002, p. 126; Ludwig & Schneider, 2006, p. 347). So far, however, there has been little discussion about alternative methods for representing the altitudinal zonation of geospatial data.

3. Study area and data

The Macaronesia is a biogeographical region comprising several archipelagos in the Atlantic Ocean, extending outwards from the coast of Europe and Africa (Fernández-Palacios et al., 2011). The archipelagos belong to three countries: Portugal, Spain, and Cape Verde. The four most densely populated Macaronesian islands of Portugal and Spain were selected as study areas: São Miguel, Madeira (both belonging to Portugal), Gran Canaria, and Tenerife (both belonging to Spain).

To acquire data, this study resorted to two public domain datasets: "CORINE land-cover 2006" (CLC2006) and the "ASTER global digital elevation model version 2" (GDEM2). CLC2006 is a land cover map of the European landscape based on remote sensing. CLC2006 is the third European land cover inventory after 1990 and 2000. These public domain datasets (http://www.eea.europa.eu/data-and-maps) provide an inventory of land cover classes organized hierarchically in three levels as a comparable cartographic product (25 ha minimum mapping unit). In addition, GDEM2 with a pixel size of 30 m, a joint product developed by Japan and US, was acquired (http://reverb.echo.nasa.gov/) and used for deriving the topographic variables altitude (m), slope (°), and aspect (°).

4. Methods

In order to display attribute and geographic space, and following earlier work (Rodrigues, 2016), the first step in the method identifies the islands' geometric center through its centroid. Second, with the origin in the islands' centroid, the islands were divided in eight geographic sectors (Figure 1(a)). A geographic division into *n* sectors can be made by dividing a landscape into the *n* wanted sectors, with the origin in the landscape's centroid. These eight geographic sectors represent the secondary-intercardinal directions. This approach was chosen following earlier work (Rodrigues, 2016), because it is flexible enough to divide any landscape into *n* sectors representing compass directions, the number of which is research-dependent.

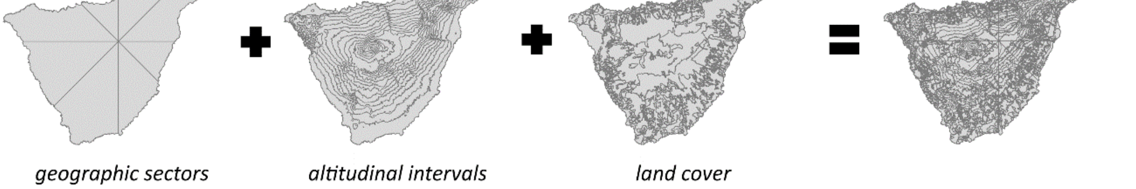

Figure 1. Example of the data intersection for the island of Tenerife.

Afterwards, to establish the altitudinal belts, the elevation data was categorized in 200 m intervals from the DEM, and converted to a vector file (Figure 1(b)). It is important to note that, depending on the research, these altitudinal belts can have any value. It was decided to use a 200 m altitudinal interval with no particular motive other than showcasing the method. CLC2006 areal units (Figure 1(c)) were then intersected with the two previous files. The result of this process (Figure 1(d)) shows in each of the eight geographic sectors, 200 m altitudinal intervals filled with land cover areal units. The aim of this procedure was to compute the proportion (%) of land cover classes in each of the 200 m altitudinal intervals within the eight geographic sectors. This was conducted by summarizing the total hectares per land cover class by altitudinal interval and by geographic sector, from the intersection of the three files (Figure 1(d)). The proportions were calculated as:

*(land cover class area of the altitudinal interval in each geographic sector * 100) / total area of the altitudinal interval in each geographic sector*

For graphically representing the eight geographic sectors into which the islands were divided, squares representing the 200 m altitudinal intervals were arranged in the same compass directions as the geographic sectors (Figure 2(a)). The square-structured approach was chosen, as this allows using the same orderly structure present in tables, allowing an effective disposition of data and transposing it to a spatially explicit representation. The disposition of the squares mimics the spokes of a traditional radar chart comprising a sequence of equi-angular spokes. Therefore, the relative position and angle of the AZRC's axes represent the compass directions. This method allows using the cyclic structure of a radar chart, where the first and last axes are placed next to each other.

Thus, the AZRC's 360 degrees correspond to compass directions in a natural and spatially explicit structure.

Intersecting the geographic sectors (Figure 1(a)), with the altitudinal belts (Figure 1(b)), results in a vector file that identifies each altitudinal interval by geographic sector. This approach allows calculating zonal statistics, thus summarizing any possible quantitative surface to be represented in the AZRC. This study has represented the majority aspect and the average slope at each 200 m altitudinal intervals. Majority aspect is depicted by the direction of an arrow in the center of each altitudinal square (Figure 2(b)). To ease the visual identification of the slope, it was chosen to proceed to a fourfold classification of the average values. The average slope in each altitudinal interval was symbolized using Jenks' (1967) natural breaks classification method (Figure 2(c)), one of the most widely used classification method for statistical mapping. However, this choice is research-dependent, thus any other classification scheme could have been used.

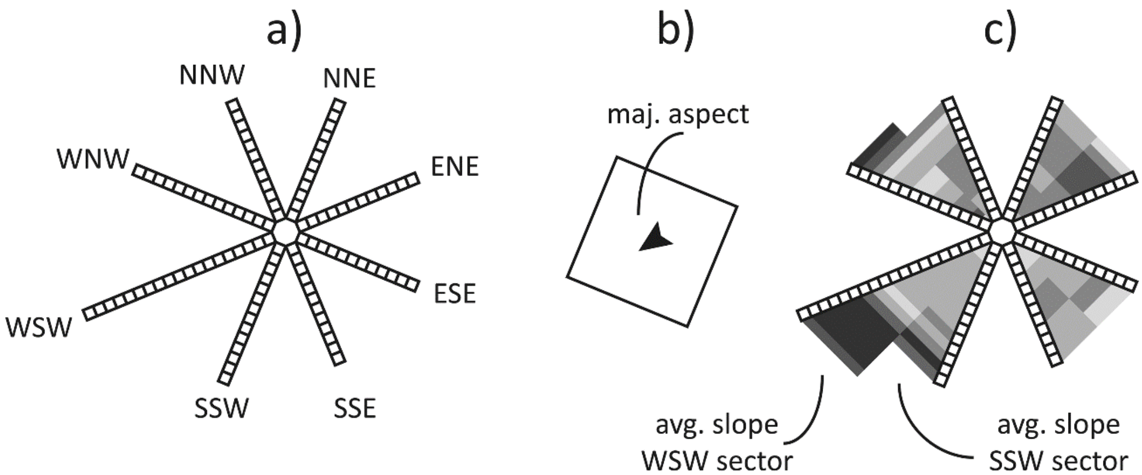

Figure 2. AZRC's foundation for the island of Tenerife.

On completion of land cover statistics, it was possible to proceed to the graphical representation of the proportion of land cover class per altitudinal interval in each geographic sector. Thus, the proportion (%) that each land cover class takes is represented in the AZRC's altitudinal squares (Figure 3(a)). It is important to note that the colors in the altitudinal squares are proportional to the frequency of the data. The method last step involves plotting altitudinal limits. This is one of the AZRC's advantages, because it allows identifying altitudinal edges connecting the altitudinal squares of higher altitude where a variable of interest occurs (Figure 3(b)). It is the same principle as in a normal radar chart, where a line is drawn connecting the data values for each spoke. Because this study used eight geographic sectors, if some land cover class has the same altitudinal edge in every geographic sector, it will cause a symmetrical altitudinal limit in the shape of an octagon.

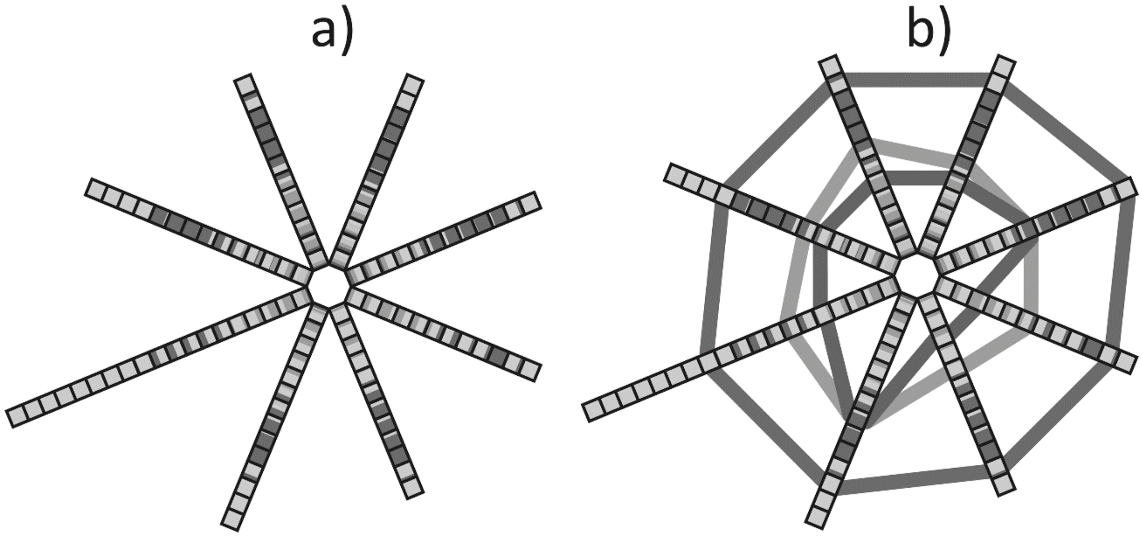

Figure 3. Tenerife's altitudinal land-cover proportions (a) and altitudinal limits (b).

4.1. Map design

The supplemental map was designed with a key element: a land-cover legend. This legend is central to the map and applies to every data-view. The map has four standard cartographic representations depicting land cover in the islands. These four standard cartographic representations are augmented through the map's novel geographic visualization approach: the AZRC presented in this article. Because the map depicts the altitudinal zonation, the data views framing the AZRCs have been designed with a simple isometric perspective that adds some sense of depth, simulating that the AZRCs are placed over the standard cartographic representations. For the typography, the map uses the Calibre font.

5. Discussion

Figure 4 shows an AZRC extracted from the supplemental map. The points of the compass are the foundation of the AZRC, hence it allows a spatially explicit representation of geospatial data. The two top rectangular spikes correspond to the north-northwest and north-northeast sectors, and so on.

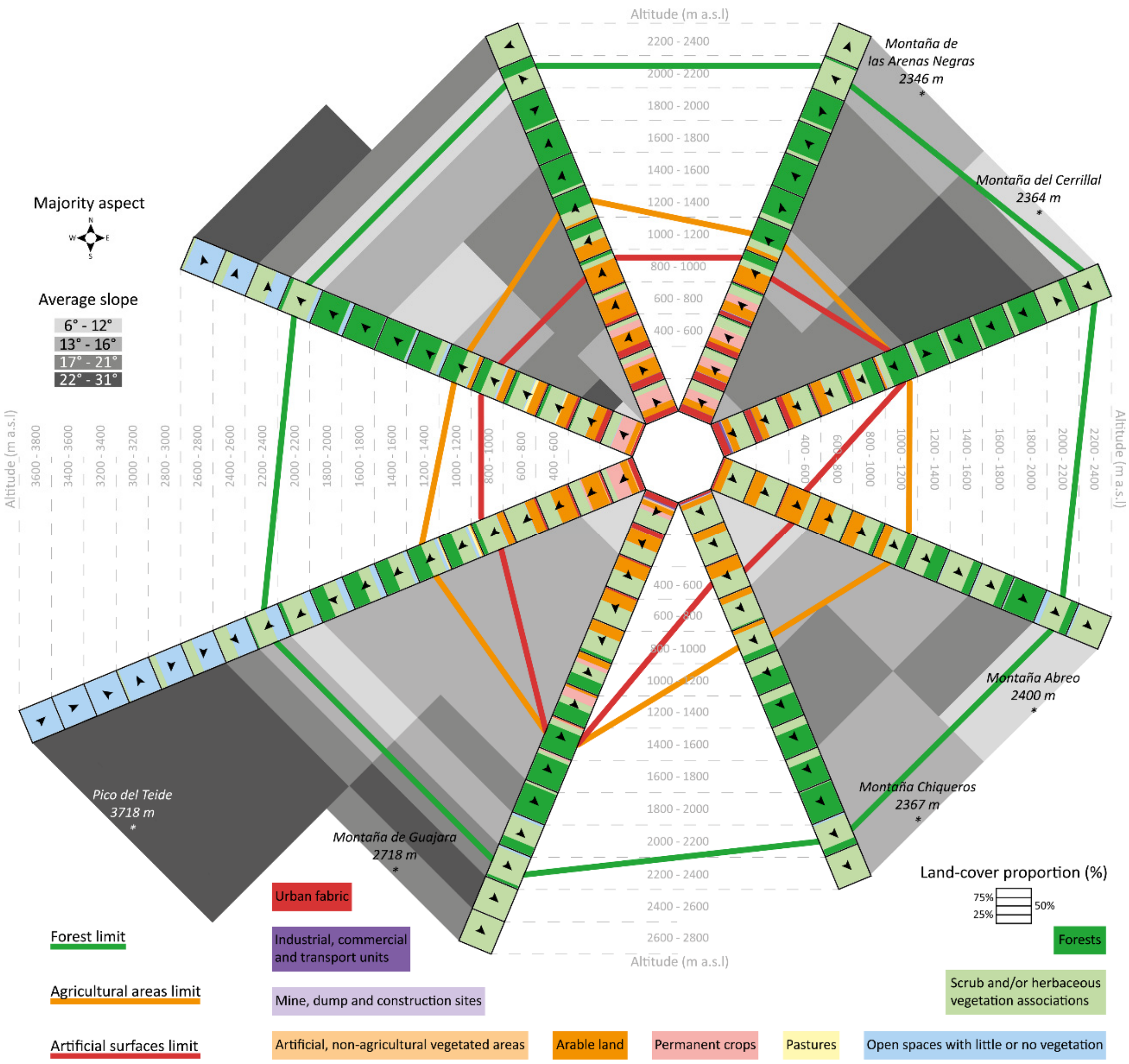

Figure 4. Tenerife's land-cover AZRC in 2006.

The AZRC creates a representation of geospatial data in both attribute and geographic space. Although this study plots three variables (i.e., land cover, slope, and aspect), the method can be customized to simultaneously display other quantitative variables, such as, evapotranspiration rates, soil properties, temperature, and rainfall, among others. An AZRC is organized as follows; the intersection of an altitudinal square with its closest axis (i.e., x- and y-directions), defines an altitudinal interval. Therefore, each altitudinal square represents an altitudinal interval in the landscape. The altitudinal squares with the same altitudinal interval define an altitudinal belt. The altitudinal squares in the AZRC's center represent the first altitudinal belt (0-200 m in this study). Departing from the AZRC's center, each parallel altitudinal square increases the altitude gradient. The geographic sector with highest altitude will have the largest radial axis. In Tenerife (Figure 4) this occurs in the WSW sector ("Pico del Teide", 3718 m a.s.l).

It is important to note that, the outer edges of the spokes represent the highest altitudes, and the center has the lowest areas. This design is due to the dissimilar maximum altitude among the compass directions represented by the spokes. In order to display the highest altitudes in the center, some altitudinal squares would have to be void of data, because a given altitudinal interval might not be present in all the spokes across the AZRC. This would make the data view unnecessarily large due to the several altitudinal intervals void of data. If all the spokes had the same maximum altitude, then it would make no difference if the altitudinal gradient started to rise in the center or in the edges. However, with dissimilar maximum altitudes across the spokes, such as in Figure 4, if one was to represent the highest altitude in the center this would render impossible to have the horizontal and vertical axis crossing at the same altitudinal interval across all the spokes without having several blank altitudinal squares. Thus, this design allows the axes to cross at the same altitudinal interval in every spoke, whilst keeping the data view as compact as possible. Because of this approach, the lowest areas are represented in the center and the largest spoke represents the highest altitude in the landscape (Figure 4).

Each pair of "altitudinal square/radial sector" is an independent data analysis unit, e.g., in this study, the north-northeastern sector has twelve data analysis units; the first one is named "0-200 NNE" and the last "2200-2400 NNE". This allows identifying every area in the AZRC. Each data analysis unit can have information represented in its altitudinal square (e.g., land cover proportion and majority aspect) or radial sector (e.g., average slope). Through the data analysis units, the selected approach reduces the dimensionality of the initial data by allowing the application of common statistical techniques or linear and nonlinear dimensionality reduction techniques. Thus, each AZRC's data analysis unit can display high-dimensional data, summarized through ratios, averages, indicators, etc. Additionally, this allows qualitative geospatial data (e.g., land cover polygons) to be converted to quantitative data (e.g., land cover proportions). Moreover, because it is a custom-made chart, data may be plotted following Bertin's ([1967] 2010) "retinal variables": size, value, texture, color, orientation, shape. Geographic labeling can also be overlaid directly on the AZRC to further aid information extraction.

The AZRC's design has the advantage of equalizing areas across a landscape, because every area depicted has the same size and shape, this avoids the misleading impression given by large vs small areas. The proposed method has another important advantage. When defined regions are important to a discussion, the default geographic unit of the observational data constrains extant methods. In extant methods, data can be displayed based on statistical aggregation over previously defined regions (e.g., counties, states, regions). Additionally, with cartographic approaches, one could use a grid to partition the data and define n regions. Nonetheless, the former approach has the drawback of relying on administrative boundaries that may not be available for a given landscape or scale. The latter approach implies placing an arbitrary grid over the data, which may be difficult to relate to the landscape because it has no geographical meaning. From this standpoint, the AZRC is more than just a visualization method, because it also represents a framework for landscape analysis. The AZRC's units are easy to interpret in the field, because they represent an altitudinal interval with a given geographic direction. In the proposed method, the coupling between the advantages of standard static displays (i.e., radar chart) with a spatial explicit geometric structure leverages the strength from standard static displays and spatial explicit geometric structures methods, facilitating a visual exploration of spatial patterns across a landscape. Naturally, in doing so, the proposed method sacrifices much of the spatial explicit accuracy of traditional cartographic approaches.

As for the AZRC's shortcomings, first, there is a loss of information, which is inevitable when representing summarized data. The disadvantage, especially for explorative visualization, is that through the loss of information, potential patterns of some attributes might be lost. Second, it requires vast amounts of tabular data to be decoded. Nonetheless, the biggest drawback is that, as it stands, the method is a time-consuming manual data encoding effort. The AZRCs in the supplemental map were built from scratch using a vector graphics editor, as charting applications do not provide specific tools for spatial diagrams.

6. Conclusions

This article presented a novel 2D static graph-based method named Altitudinal Zonation Radial Chart (AZRC). The proposed method allows displaying high-dimensional geospatial data in a single data view, in both attribute and geographic space. The supplemental map confirms that the method can create a representation of the altitudinal zonation of geospatial data, whilst minimizing visual effectiveness issues. The AZRC can: (1) Preserve the spatial relationships between individual data analysis units while retaining the overall view of the entire landscape. (2) Facilitate visual comparisons among study areas and/or time-series. (3) Convey and enhance the understanding of geospatial data in a spatially explicit and meaningful manner, to uncover underlying spatial patterns and trends. (4) Be a framework for landscape analysis, because the AZRC's units represent an altitudinal interval with a given geographic direction. Thus, the method avoids resorting to an artificial partition of the landscape, sometimes difficult to relate to the reality on the field. As for future work, the proposed method calls for an automated tool, to streamline the time-consuming manual work needed to create an AZRC.

7. Software

Spatial analysis and data manipulation were accomplished with ArcGIS® Desktop 10, and map layouts exported to the Illustrator® file format. Land cover statistical analysis was performed with Excel® 2013. Composition, charting and labelling were all made with Illustrator® CS6.

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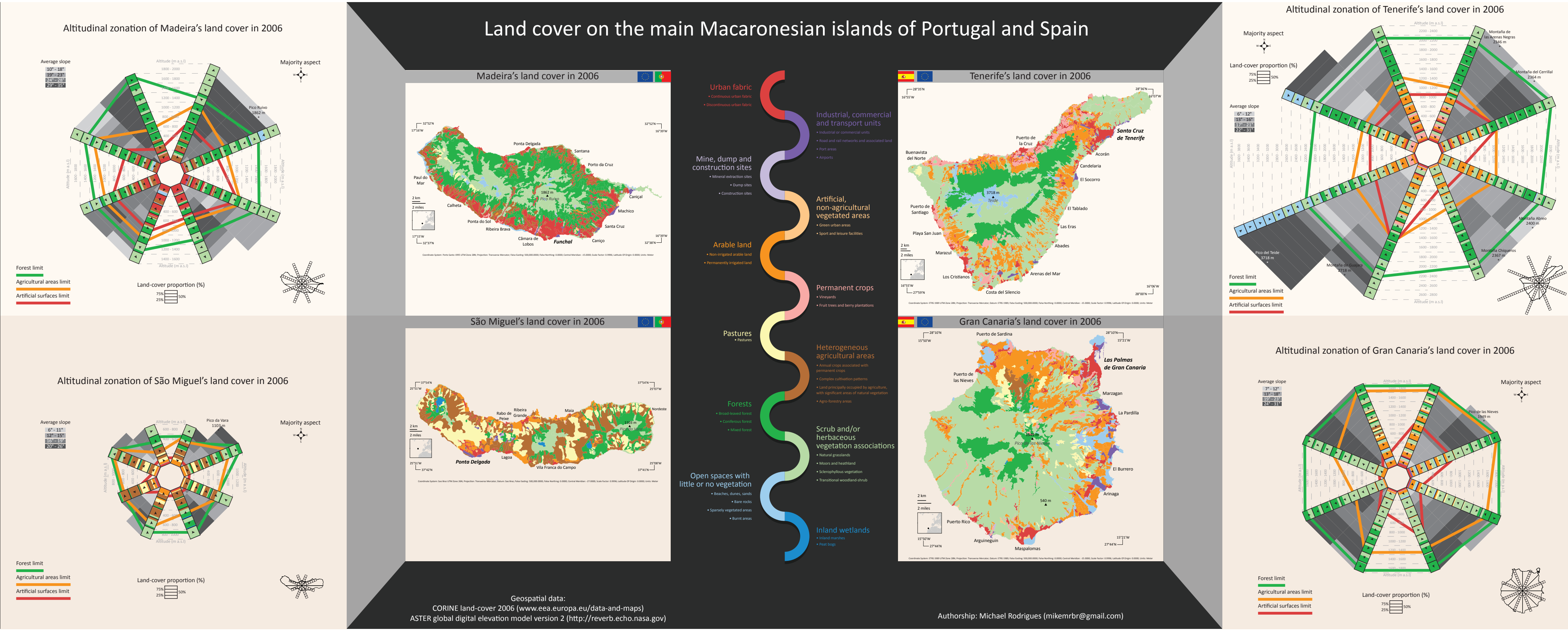
Land cover on the main Macaronesian islands of Portugal and Spain
Altitudinal zonation of Madeira's land cover in 2006
Average slope
Majority aspect
Pico Ruivo 1862 m
Forest limit
Agricultural areas limit
Artificial surfaces limit
Land-cover proportion (%)
Madeira's land cover in 2006
Ponta Delgada
Santana
Porto da Cruz
Paul do Mar
Caniçal
Machico
Santa Cruz
Calheta
Ponta do Sol
Ribeira Brava
Câmara de Lobos
Funchal
Caniço
1862 m
Pico Ruivo
2 km
2 miles
32°52'N
16°39'W
32°38'N
Altitudinal zonation of São Miguel's land cover in 2006
Average slope
Majority aspect
Pico da Vara 1103 m
Forest limit
Agricultural areas limit
Artificial surfaces limit
Land-cover proportion (%)
São Miguel's land cover in 2006
Rabo de Peixe
Ribeira Grande
Maia
Nordeste
Ponta Delgada
Lagoa
Vila Franca do Campo
2 km
2 miles
25°07'W
25°08'W
Urban fabric
• Continuous urban fabric
• Discontinuous urban fabric
Industrial, commercial and transport units
• Industrial or commercial units
• Road and rail networks and associated land
• Port areas
• Airports
Mine, dump and construction sites
• Mineral extraction sites
• Dump sites
• Construction sites
Artificial, non-agricultural vegetated areas
• Green urban areas
• Sport and leisure facilities
Arable land
• Non-irrigated arable land
• Permanently irrigated land
Permanent crops
• Vineyards
• Fruit trees and berry plantations
Pastures
• Pastures
Heterogeneous agricultural areas
• Annual crops associated with permanent crops
• Complex cultivation patterns
• Land principally occupied by agriculture, with significant areas of natural vegetation
• Agro-forestry areas
Forests
• Broad-leaved forest
• Coniferous forest
• Mixed forest
Scrub and/or herbaceous vegetation associations
• Natural grasslands
• Moors and heathland
• Sclerophyllous vegetation
• Transitional woodland-shrub
Open spaces with little or no vegetation
• Beaches, dunes, sands
• Bare rocks
• Sparsely vegetated areas
• Burnt areas
Inland wetlands
• Inland marshes
• Peat bogs
Tenerife's land cover in 2006
28°35'N
16°55'W
Santa Cruz de Tenerife
Puerto de la Cruz
Buenavista del Norte
Acorán
Candelaria
El Socorro
3718 m
Teide
Puerto de Santiago
El Tablado
Las Eras
Playa San Juan
Abades
Marazul
Los Cristianos
Arenas del Mar
Costa del Silencio
2 km
2 miles
16°55'W
27°59'N
Gran Canaria's land cover in 2006
Puerto de Sardina
Las Palmas de Gran Canaria
Puerto de las Nieves
Marzagan
La Pardilla
El Burrero
Arinaga
Puerto Rico
Arguineguin
Maspalomas
540 m
2 km
2 miles
15°50'W
Altitudinal zonation of Tenerife's land cover in 2006
Majority aspect
Land-cover proportion (%)
Average slope
Montaña de las Arenas Negras 2346 m
Montaña del Cerrillal 2364 m
Montaña Abreo 2400 m
Montaña Chiqueros 2367 m
Montaña de Guajara 2718 m
Pico del Teide 3718 m
Forest limit
Agricultural areas limit
Artificial surfaces limit
Altitudinal zonation of Gran Canaria's land cover in 2006
Average slope
Majority aspect
Pico de las Nieves 1949 m
Forest limit
Agricultural areas limit
Artificial surfaces limit
Land-cover proportion (%)
Geospatial data:
CORINE land-cover 2006 (www.eea.europa.eu/data-and-maps)
ASTER global digital elevation model version 2 (http://reverb.echo.nasa.gov)
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GIS-based modeling of a rescaled surface of land development pressure in the Macaronesian islands

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Land development is one of the major anthropogenic processes shaping environmental sustainability. However, no standard method exists for evaluating this spatial process. This article proposes a method of modeling a spatially explicit representation of land development pressure, resorting to an inverse distance weighting interpolation. The study area encompasses four Macaronesian islands where land development has caused dramatic changes to the landscape: São Miguel, Madeira, Gran Canaria, and Tenerife. The method is demonstrated over 1990–2006, a period marked by a rapid increase in land development which ended with the 2007–2008 financial crisis. First, centroids of land change in/into artificial surfaces were used as a proxy of land development pressure. Second, these centroids were coupled with ancillary sampled points, which took into account a topographic resistance factor representing areas absent of land change. These ancillary points allowed for confinement of the interpolation values while acting as structural information for the rescaling of the interpolation into a higher resolution of a digital elevation model. The results show that the method captured the overall trend and magnitude of artificial land change. Quantifying and identifying the islands' pattern of land development pressure creates a variable that can play an important role in further modeling of anthropogenic spatial processes.

Keywords: land change; interpolation; rescaling; geostatistics; Macaronesia

1. Introduction

The increased awareness on issues related to environmental sustainability, confronted with intensifying land development, has increased the importance of land-use/land-cover (LULC) change assessment (Wickham, O'Neill, and Jones 2000; Jaimes et al. 2010; Peneva-Reed 2014). There is consensus that land development is one of the major anthropogenic processes shaping environmental sustainability (Jarnagin 2004; Berlanga-Robles and Ruiz-Luna 2011; Cunningham et al. 2015; Abdullahi et al. 2015). In addition, research recognizes the need to identify, quantify, and explain LULC driving forces (Christman et al. 2015). However, no standard method exists for quantifying and evaluating a spatially explicit representation of land development pressure. To support planning and decision-making, one of the key applications of geographical information science relies in geospatial modeling (Estoque and Murayama 2014). In this regard, a modeled surface of land development pressure can play an important role as an explanatory

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variable, further modeling a multitude of environmental, social, and economic processes. Therefore, this article proposes a geographical information science-based method of mapping land development pressure suitable for application elsewhere.

In the last decades, human-induced landscape changes were profound at a global scale (Foley et al. 2005). These changes have also affected the small and isolated Macaronesian islands of Portugal and Spain. Over the last few decades, fast growing tourism activity has caused dramatic changes to the islands' landscape. Because of limited land and geographical isolation, the land-change process is magnified in comparison with mainland regions. Moreover, due to the islands' ecological importance (Fernández-Palacios et al. 2011), land-change studies are of particular significance to this region. For that reason, this article uses four Macaronesian islands to showcase the proposed method of modeling a spatially explicit representation of land development pressure.

Land change can be perceived as a geographically complex system, represented by intricate interactions between man and nature (Pijanowski et al. 2002; Jarnagin 2004; Berlanga-Robles and Ruiz-Luna 2011), which "interact dynamically to give rise to different sequences and trajectories of change" (Nagendra, Munroe, and Southworth 2004, 114). LULC driving forces are the outcome of these complex interactions, from which LULC change is the visible impact on the landscape (Jarnagin 2004). Consequently, LULC driving forces affect the entire landscape, rather than only where land change had occurred. From this perspective, this study is built upon two assumptions. The first one is that any landscape can fit into a land development gradient, with a magnitude ranging from zero (i.e., no change/lowest pressure) up to the observed maximum land change (i.e., maximum change/highest pressure) on the landscape. This assumption integrates particularly well with interpolation techniques, which produce continuously varying surfaces represented by the raster data model (Burrough 2001). Because land-change outcomes arise from LULC driving forces (Nagendra, Munroe, and Southworth 2004; Long et al. 2007; Jaimes et al. 2010), the study's second assumption is that the size of artificial land-change areal units can provide a means to deduce land development pressure. As a result, these assumptions allow for the use of land change in/into artificial surfaces as a proxy for land development pressure. Nonetheless, it is important to note that, although land development is a key component of the urbanization process, this article refrains from applying the terms "urban" or "urbanization." The urban dimension implies additional data other than biophysical coverage. Therefore, in this article, "land development" is defined as a change in the biophysical coverage of land in/into artificial surfaces, which might or might not have occurred in urban areas.

Research has shown several applications of interpolation algorithms on approaches to deduce spatial anthropogenic impacts (Wickham, O'Neill, and Jones 2000; Wu and Murray 2005; Varanka 2010; Temme and Verburg 2011). For instance, Wickham, O'Neill, and Jones (2000) generated a surface of "demand for land" through splining interpolation of a ratio of population over distance. Wu and Murray's (2005) technique applied a cokriging method to interpolate population density by modeling the spatial correlation and cross-correlation of population and impervious surfaces. Varanka's (2010) study presented a spatial trend surface representing "population pressure on the environment." The author derived this surface from a kriging interpolation of a variable meant to be a proxy of human consumption of material resources based on per capita income and population density. More recently, Temme and Verburg (2011) resorted to CORINE land-cover (CLC) datasets to distribute "agricultural land-use intensity" for years 2000 and 2025. Temme and Verburg's (2011) method maps the current spatial distribution of "agricultural land-use intensity" and predicts the possible outcomes from policy effects to assess the probability of occurrence for three intensity classes.

The present study also uses the public domain CLC datasets. These European land-cover datasets are available in 100 m resolution grids. However, the spatial resolution of the most widely available remote sensing data in the Macaronesian islands is 30 meters (i.e., LANDSAT imagery). Therefore, a rescaling process would provide a more precise allocation for the modeled surfaces that would be better adapted to carrying out further studies. To address the lack of higher resolution data, methods for "rescaling landscape data are frequently required to assess patterns of landscape change through time and over large areas" (Gardner et al. 2008, 513). Refining the analysis often requires spatial rescaling (Van Vuuren, Smith, and Riahi 2010), a process where information at coarse scale is translated to detailed scales while maintaining consistency with the original dataset (Boucher and Kyriakidis 2006). On this matter, several studies have resorted to LULC rescaling methods to allow data to be "primarily rescaled from the national or regional scale to a spatial resolution appropriate for environmental impact analysis" (Britz, Verburg, and Leip 2011, 40). For instance, Verburg et al. (2006) rescaled land use changes from macroscale models to the landscape level. The authors aimed to rescale European level scenarios of future change in political and socioeconomic conditions to a resolution suitable for detecting landscape change. Boucher and Kyriakidis (2006) used a cokriging indicator to approximate the probability that a pixel at a higher spatial resolution belongs to a particular land-cover class, given the coarse resolution fractions and a sparse set of higher resolution land cover. More recently, West et al. (2014) rescaled global land-cover projections to be used in regional analysis at higher resolutions. The authors advocate that because projections of land-cover change are often estimated at a coarse scale, rescaling these estimates is necessary to align the land-cover change estimates with other higher resolution variables.

Assessing land development pressure leads to several research questions, which this article aims to answer: (1) how can the highest pressure sites be identified using land development?, (2) what is the islands' pattern of land development pressure?, and (3) which areas were prone to land development? This study addresses these three questions for four Macaronesian islands, quantifying and identifying the islands' pattern of land development pressure. Moreover, while contributing to address the islands' lack of uniform and comparable data, this article has two objectives. The first objective is to model an interpolated spatial surface by resorting to a method where land change in/into artificial surfaces was used as a proxy of land development pressure. The second objective is to rescale the interpolated coarse CLC-derived data into the 30 m spatial resolution where a multiplicity of remote sensing data are available for the islands.

2. Study area and data

Macaronesia is a biogeographical region comprising several archipelagos in the Atlantic Ocean, extending outwards from the coast of Europe and Africa (Fernández-Palacios et al. 2011). The archipelagos belong to three countries: Portugal, Spain, and Cape Verde. Four Macaronesian islands were selected as the study area: São Miguel, Madeira (both belonging to Portugal), Gran Canaria, and

Tenerife (both belonging to Spain). São Miguel is the largest and most populous island in the Portuguese Azores archipelago, with, as of 2015, approximately 0.14 M inhabitants covering the 745 km^2 island. Madeira is the largest island of the Portuguese archipelago with the same name; it has an area of 759 km^2 and approximately 0.26 M inhabitants. Gran Canaria, with a surface area of 1560 km^2, is the second most populous of the Spanish Canary Islands, with approximately 0.85 M inhabitants. Finally, Tenerife is the largest and most populous of the Canary Islands archipelago; it has a surface area of 2034 km^2 and approximately 0.9 M inhabitants.

These volcanic islands present major topographic constraints for the expansion of built-up areas. As a result, the population is concentrated predominantly along the coast. Over the last few decades, tourism development and its associated commercial and residential growth has dramatically changed the islands' landscape. This change has been recorded in LULC data. However, the Macaronesian islands have long been understudied in geographical research because of two reasons. First, their size and population denotes dynamics of lower magnitude, which might detract interest in their study. Second, there is a chronic shortage of comparable and uniform geospatial data for these islands. LULC inventories are essential to compare landscape conditions and to assess patterns of land change observed over time (Christman et al. 2015). In this regard, research recognizes the "lack of homogenous datasets, modeling, monitoring, and mapping strategies throughout the EU" (Temme and Verburg 2011, 46).

The main sources of data used in this study included the CLC datasets for 1990, 2000, and 2006 and a digital elevation model (DEM). CLC are a map of the European landscape classified from remote sensing data. These public domain datasets provide an inventory of land-cover classes organized hierarchically in three levels as a comparable cartographic product. These datasets are available in 100 m resolution grids, providing an inventory of land-cover classes, for the years of 1990, 2000, and 2006. In this study, only the first level is used, specifically the "artificial surfaces" category. Artificial land change can be studied by selecting it from the areas that changed over the years. The areas that experienced change are available for 1990–2000 and 2000–2006. Therefore, the acquired layers, "CLC 1990–2000 changes" and "CLC 2000–2006 changes" (http://www.eea.europa.eu/data-and-maps), represent those areas that experienced change. In addition, the study also used a DEM to derive topographical variables. "ASTER Global Digital Elevation Model version 2," with a pixel size of 30 m, a joint product developed by Japan and US, was acquired (http://reverb.echo.nasa.gov) and used for deriving the topographic variables such as altitude (m) and slope (°).

3. Methods

When establishing this study, several methodological challenges had to be tackled. First, because of the islands' lack of uniform geospatial data, CLC was the only uniform LULC data available. Additionally, because of the coarse resolution, there were only a small number of artificial land-change locations available. However, interpolation methods can address this issue because these techniques produce continuous surfaces deducing attribute values at unsampled locations (Burrough 2001). Therefore, the method used in this study interpolates LULC-derived data resorting to the inverse distance weighting (IDW) algorithm. Another methodological challenge was that, for many applications, CLC resolution is too coarse (100 m). A more precise allocation for the modeled surfaces would be better adapted to carrying out further studies. Thus, this study tests the application of IDW to rescale LULC-derived data, interpolating the modeled land development surfaces at a higher resolution (30 m). In doing so, a novel approach is presented, which samples ancillary points taking into account a topographic resistance factor representing the areas void of artificial land change. These ancillary sampled points doubled the interpolation locations and confined the values for the interpolated surface, while acting as "structural information" for the rescaling process (Boucher and Kyriakidis 2006). It is important to note that, in this study, geographical modeling was applied to present a historical (1990–2006) spatial trend surface as an interpolated variable of land development pressure. As enumerated by Epstein (2008), there is a multitude of reasons for geographical modeling other than prediction. Therefore, the aim of this study's model is to help explain the present, rather than predict future scenarios.

The method's first step consisted in selecting only the areas that experienced change in/into artificial surfaces from "CLC 1990–2000 changes" and "CLC 2000–2006 changes" datasets (http://www.eea.europa.eu/data-and-maps). These areas are clearly identified in the database. To acquire samples for interpolation, centroids were extracted from these selections of artificial land change and merged into a single dataset representing "artificial CLC 1990–2006 changes." These centroids maintain the alphanumeric attributes of their areal units. As a result, the variable "hectares" was used in the interpolation. A statistical summary of the "artificial CLC 1990–2006 changes" centroids is presented in Table 1. The majority of the centroids were derived from small area polygons, as shown in Table 1. This affects the normality of the distribution. It is important to take into account that the values that appear as outliers in the data are of most interest to the analysis of land development pressure. In this regard, an IDW interpolation assumes no particular distribution of the data (Burrough and McDonnell 1998), hence the outliers could be kept in the dataset.

3.1. Data preparation

To confine the interpolation to contain the lowest values of land development pressure (i.e., no land change/lowest pressure), it was necessary to use ancillary sampled locations assigned with values of zero hectares. These locations were sampled across a constraining area defined by a topographic resistance factor derived from the DEM. As Gardner et al. (2008, 524) note, the "structure of landscape patterns may provide the best means of identifying an optimal sampling net." The topographic resistance factor layer is meant to represent areas with no artificial land

Table 1. Summary statistics of the artificial CLC changes in 1990–2006 for the four islands.

	N	Min. (ha)	Max. (ha)	Mean (ha)	Median (ha)	*SD* (ha)	Skewness (ha)
São Miguel	48	5.06	34.52	12.54	8.83	8.41	1.18
Madeira	253	0.72	172.74	17.64	0.46	24.15	4.15
Gran Canaria	65	5.88	505.01	46.07	30.80	64.45	5.81
Tenerife	114	3.48	149.87	24.55	14.43	21.09	2.24

change in the CLC data and allow restriction of the interpolation. This strategy doubled the observed data locations and assisted the rescaling process.

Because of their volcanic origin, there are significant topographic factors influencing geographic modeling in these islands. However, selecting an appropriate altitude and slope resistance factor to include in the model can be an arbitrary process. Therefore, the approach this study took into account was the observed maximum altitude and slope in the "artificial CLC 1990–2006 changes" centroids in each island (Table 2). The areas below the observed maximum altitude and slope were classified from the DEM to create a constraining area for sampling. The areal units of "CLC 1990–2000 changes" and "CLC 2000–2006 changes" were also added to this constraining layer in order to not have sampled points allocated inside artificial land-change areal units. Thus, the ancillary sampled points are sampled only in the areas outside the artificial land-change areal units and across the landscape below the observed maximum altitude and slope in the centroids of artificial land change. When sampling the points inside this constraining layer, points were automatically assigned a value of zero hectares. However, it is important to note that this topographic resistance factor might not hold true in homogenous landscapes where topography does not play a key role in land development pressure.

Regarding sampling design, a stratified random sampling, using island as strata, generated randomly placed points across the constraining area defined by the topographic resistance factor. These randomly sampled points, with an assigned value of land development pressure of zero (i.e., no artificial land change), were merged with the "artificial CLC 1990–2006 changes" centroids. Table 3 shows the summary statistics for the final point dataset, integrating the "artificial CLC 1990–2006 changes" centroids and the randomly generated samples, restricted by altitude and slope observations.

Table 2. Maximum altitude (m) and slope (°) of artificial CLC change in 1990–2006 for the four islands.

	Maximum altitude (m) in "artificial CLC 1990–2006 changes" centroids	Maximum slope (º) in "artificial CLC 1990–2006 changes" centroids
São Miguel	222	19
Madeira	1144	49
Gran Canaria	471	21
Tenerife	625	26

Source: Calculated from the digital elevation model.

Table 3. Summary statistics of final dataset used in the interpolation for the four islands.

	N	Min. (ha)	Max. (ha)	Mean (ha)	Median (ha)	*SD* (ha)	Skewness (ha)
São Miguel	96	0	34.52	6.27	2.53	8.64	1.55
Madeira	506	0	172.74	8.88	0.36	21.01	4.86
Gran Canaria	130	0	505.01	23.04	2.94	50.95	6.89
Tenerife	228	0	149.87	12.27	1.74	17.27	2.84

3.2. Interpolation and cross-validation

In 1989, Bracken and Martin generated population surface models using the IDW algorithm to interpolate point values and develop a population surface. In Bracken and Martin's (1989) method, population counts are assigned to a set of summary points generated from the centroids of the areal units. Bracken and Martin's (1989) method assumes that population density decreases away from the census enumeration districts centroids according to some distance-decay function. This allows for some areas of the raster surface to contain zero population. The present study sought to use the values of coarse scale-measured locations (i.e., CLC artificial land change) to presume the land development pressure of higher resolution unmeasured locations. For this reason, the proposed method also uses the IDW interpolator, allowing land development pressure to decrease from the observed artificial land-change centroids. Similar to Bracken and Martin's method (1989), the modeled surface in this study allows values of zero, that is, areas of no artificial land change/lowest pressure.

IDW is one of several interpolation methods for generating surfaces from discrete data (Burrough and McDonnell 1998). The basic formulation for an IDW interpolation is,

$$u(x_0) = \left[\sum_{i=1}^{n} u(x_i)/(d_i^p)\right] \Big/ \left[\sum_{i=1}^{n} 1/(d_i^p)\right],$$

where $u(x_0)$, $u(x_i)$ represent the predicted (interpolated) and observed (interpolating) value at location x_0, x_i; n is the total number of sample points within a defined neighborhood from x_0 to x_i; p is the power parameter, a positive real number, and d_i is the distance from x_0 to x_i.

The applied IDW interpolation directly implements the assumption that a value at an unsampled location (i.e., unknown land development pressure) is a weighted average of known data points (i.e., hectares of artificial land-change areal units). The computation is constrained within a local neighborhood surrounding the unsampled location, in which the weighting function is the inverse of distance raised to a power parameter (Burrough and McDonnell 1998). As a result, the model assumes that the sampled points represent minimum and maximum land development pressure. This is based on the principle that sample values (i.e., hectares of artificial land-change areal units) closer to the interpolated location have more influence on land development pressure than sample values farther apart. Therefore, IDW interpolation was well suited for the first methodological issue: how to create a surface gradient from a few sample locations.

To assist with finding the optimal interpolation parameters, cross-validation was used to find the best agreement between the measured data and the IDW estimates. In this study, IDW interpolated surfaces were estimated with power parameters of one, two, and three. The number of samples used for estimation varied from five to twenty, acting to limit the extent of the data used to determine the value of an unknown location. Optimization of the interpolation parameters used the following systematic approach: (1) vary the exponential power parameter (one to three) and the number of samples (five to twenty), then apply a cross-validation procedure, (2) use the root mean square error (RMSE) to identify a set of interpolation parameters that yield the lowest error, and (3) generate an island-wide surface of land development pressure.

3.3. *Goodness-of-fit measures*

This step in the method compared modeled land development pressure values with the observed size (hectares) of the artificial land-change areal units. This allowed for assessment of whether the modeled surface truly carried information on the observed artificial land-change areas. According to reference literature (Bossard, Feranec, and Otahel 2000), sample size was computed as a standard validation of CLC, aiming at an accuracy of 85% at the 95% confidence level. The 196 samples obtained were rounded up to 200 sample points, which were created for a simple random sampling. Therefore, in each island, a random set of 200 points was created inside the areal units of "artificial CLC 1990–2000 changes," "artificial CLC 2000–2006 changes," and "artificial CLC 1990–2006 changes." The hectares of the areal units were used as reference data. Afterwards, the surface values of land development pressure were extracted from the sampled points and were labeled against the reference data. This allowed for a comparison between the 30 m interpolated land development pressure surface and randomly sampled points from the interior of coarser artificial land-change areas over a three time series. This comparison evaluates whether the modeled land development pressure is distributed in a manner that matches the trend in artificial land change.

4. Results and discussion

4.1. *Interpolation and cross-validation*

To answer the first research question: how can the highest pressure sites be identified using land development? The proposed method resorted to an interpolation of centroids derived from artificial land-change areal units. The areal size provides an indirect measurement to land development pressure. Aiming to find the optimal interpolation parameters, cross-validation was used to find the best agreement between measured data and IDW estimates. The results based on cross-validation parameters are summarized in Table 4.

In the interest of finding the optimal interpolation parameters, the surface producing the lowest RMSE was considered as the least biased model (Table 4). RMSE is a summary statistic quantifying the error of the modeled surface, using the units of the response variable (i.e., hectares). The results indicate that increasing the power parameter

Table 4. Cross-validation for different combination of IDW parameters using RMSE (ha).

Power	Samples	São Miguel	Madeira	Gran Canaria	Tenerife
1	5	8.24	22.30	54.29	18.44
	10	8.42	21.00	51.63	17.61
	15	8.27	20.87	51.22	17.09
	20	8.17	20.70	51.19	16.94
2	5	8.36	22.95	56.48	19.25
	10	8.50	21.94	54.07	18.57
	15	8.45	21.74	53.39	18.24
	20	8.41	21.58	53.06	18.08
3	5	8.47	23.62	59.14	20.04
	10	8.58	23.01	57.09	19.60
	15	8.56	22.89	56.47	19.44
	20	8.56	22.82	56.15	19.36

produces a larger RMSE, despite the outcome of a smoother surface. In addition, in the case of this study, as shown in Table 4, increasing the number of samples decreased the RMSE. Consequently, if more neighboring data points were used, the search radius could be increased incrementally. As a result, selecting a larger number of samples helped to compensate for the effects of data clustering. Overall, as shown in Table 4, in all the cases, the best power parameter was found to be a power of one with twenty samples.

4.2. Goodness-of-fit measures

One measure commonly used for assessing model fit is the coefficient of determination R-squared (R^2). R^2 indicates the proportion of variance in the outcome that can be accounted by the model. Table 5 shows the R^2 of the differences between the observed and the modeled values ranging from 0.41 to 0.77 ($p < 0.001$). Over 1990–2000, the comparison of mapped land-change artificial surfaces to modeled land development pressure produced R^2 ($p < 0.001$) values of 0.58, 0.47, 0.41, and 0.51. Over 2000–2006, the R^2 ($p < 0.001$) values were 0.77, 0.62, 0.58, and 0.66. Taking into account the 1990–2006 period, from which the interpolations were based, correlations were similar among the islands with R^2 ($p < 0.001$) values of 0.74, 0.59, 0.54, and 0.67. Therefore, the R^2 measures show that, overall, the modeled surfaces captured the artificial land-change trend over the years.

As shown in Table 5, the RMSE of the regression summarizes the distance the modeled values are to the observed, using the units of the response variable (i.e., hectares). There is an inverse relationship between R^2 and the RMSE. Taking into account the 1990–2006 period, the RMSE of the regression for São Miguel is 2.46 hectares (Table 5). Therefore, over 1990–2006, the model is unfit, on average, by 2.46 ha in São Miguel, 10.73 ha in Madeira, 31.56 ha in Gran Canaria, and 5.98 ha in Tenerife (Table 5). In every island, compared with the 2000–2006 period, 1990–2000 results show poorer goodness-of-fit measures. This is a consequence of the 1990–2000 dataset being comprised of a large number of artificial land-change areal units with a higher dispersion of hectare values. On the other hand, the shorter 2000–2006 interval registers lower artificial land-change dynamics across the islands. This lower dynamic produced, on average, a more fitted model when compared with the 1990–2000 period. A poorer goodness of fit in Gran Canaria and Madeira was also expected (Table 5) due to a greater amount of variation and skewness in the set of interpolated data values (Table 3). Conversely, São Miguel and Tenerife had a lower dispersion and more asymmetric data values (Table 3), thus the better goodness-of-fit measures in these islands (Table 5). Furthering the analysis, Figure 1 shows the comparison of modeled and observed values for 200 observations

Table 5. Land development pressure goodness-of-fit measures (n = 200 observations).

		São Miguel	Madeira	Gran Canaria	Tenerife
1990–2000 artificial land-change areal units	R-squared	0.58	0.47	0.41	0.51
	RMSE (ha)	2.65	23.02	36.84	8.38
2000–2006 artificial land-change areal units	R^2	0.77	0.62	0.58	0.66
	RMSE (ha)	2.31	7.49	8.83	5.19
1990–2006 artificial land-change areal units	R^2	0.74	0.59	0.54	0.67
	RMSE (ha)	2.46	10.73	31.56	5.98

Note: p-value < 0.001.

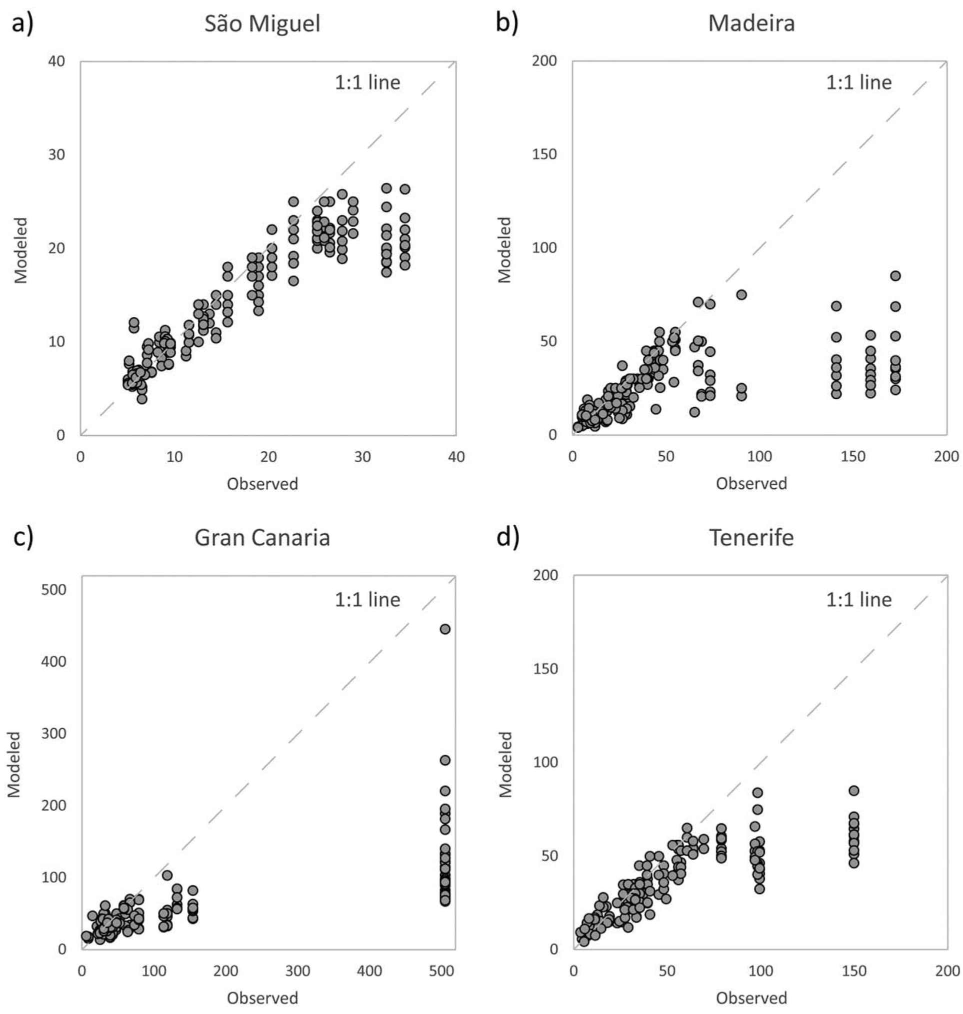

Figure 1. Comparison of modeled and observed values (ha) for 200 observation points across the artificial land-change areal units in 1990–2006.

points in the artificial land-change areal units in 1990–2006, the period from which the interpolations were based. The shift from the 1:1 line shows the bias in the model throughout the range of modeled values.

Figure 1 shows that the model over- and underpredicts the data across the four islands. Nonetheless, there is a tendency for underestimation, as shown by the predominance of sample points below the 1:1 line. In Figure 1, there are far more sample points at the lower values and a scarcity of samples at higher values. This relates directly with the normality of the distribution of data used (Table 3). In all the islands, results for the higher values show a clustered pattern due to the presence of a few outliers. Figure 1 also shows an increasing trend where there is more discrepancy in the sample points with increasing land-change values (i.e., the model performs poorly as the prediction moves from small-to-large land-change areal units). Generally, the model performs poorly in areas larger than 30 ha. A single data point, represented by the areal unit centroid, is not sufficient to model a large area, particularly when the neighboring data points from the remaining areal units have much smaller values. As a result, the model struggles to determine the land development pressure across areas dominated by outliers. It is important to note that, in the case of this study, it was essential to keep the outliers because these allow identification of very large artificial land-change areas. As such, these outliers cannot be discarded because they are paramount to the analysis of land development pressure. Among the study areas, Gran Canaria is the best example of the effect of an outlier. Gran Canaria data has an outlier with 505 ha. Figure 1(c) shows that, for the allocated points in this 505 ha artificial land-change area, the model massively under-predicts the data. Because this particular land-change area totals 505 ha, modeled values should be higher across the surface occupied by this areal unit. As the model tries to build the continuous surface, there is only one data point totaling 505 ha. However, the remaining data points have much lower values, hence the discrepancy in the surface areas dominated by outliers in every island (Figure 1).

Research indicates, "uncertainty and potential error in land-cover classification estimates may inhibit accurate assessments of land change" (Christman et al. 2015, 543). In this regard, Estoque and Murayama's (2014) study discussed the nonstationary characteristic of land-change patterns, examining its potential effect on modeling accuracy using a geospatial approach. Therefore, users of categorical land-cover products must recognize the inherent limitations for land-change analysis (Christman et al. 2015). When analyzing Table 5, it is important to note that the choice of the interpolation method can influence the model's goodness-of-fit measures. Moreover, centroids representing artificial land change tend to produce a clustered spatial coverage. This was, to some extent, mitigated when using the no-change sampled points that take into account the topographic resistance factor. Another issue affecting the goodness-of-fit measures is the distortion at the boundaries due to edge effects. Nonetheless, because the study areas were islands, this issue could not be addressed by having data shift from the study area.

It is important to note that IDW might not be the best algorithm to compute the surface of land development pressure. In future studies, the proposed method needs further assessment with different interpolation methods (e.g., Kriging, Spline, among others) to find the best results in terms of model fitting. Because the main goal of this article was showcasing the proposed method, there was no restrictive tolerance of estimation errors. Therefore, the modeled surfaces of land development pressure were considered acceptable in capturing the artificial land-change trend over the years.

4.3. Spatially explicit representation

The presented method allowed for deduction of a historical trend (1990–2006) of land development pressure based on the size of observed artificial land-change areal units. This was a period marked by a rapid increase in real-estate valuations, which ended with the financial crisis of 2007–2008. Figures 2–5 represent the 30-m resolution modeled surfaces computed with the IDW interpolation with the lowest RMSE (Table 4) and constrained by a topographic resistance factor. The figures show the computed surfaces draped over a hillshade, acquired from the same DEM used as data source. Overall, the presented figures provide a spatially explicit depiction of land development pressure represented through a gradient. These results are the basis for answering the remaining research questions: What is the islands' pattern of land development pressure? Which areas were prone to land development?

As expected, the lowest surface values, and thereby lowest land development pressure, occurred inland. As shown in the figures, the highest values are located along the coast, where the decay effect from the coastline is visible at a distance. One of the drawbacks of an IDW interpolation is the spatial "bull's eye" effect, visible as lighter or darker dots. To achieve smoother surfaces, the effect could be attenuated by changing the IDW parameters. However, this would only be possible at the cost of an increased RMSE error. On

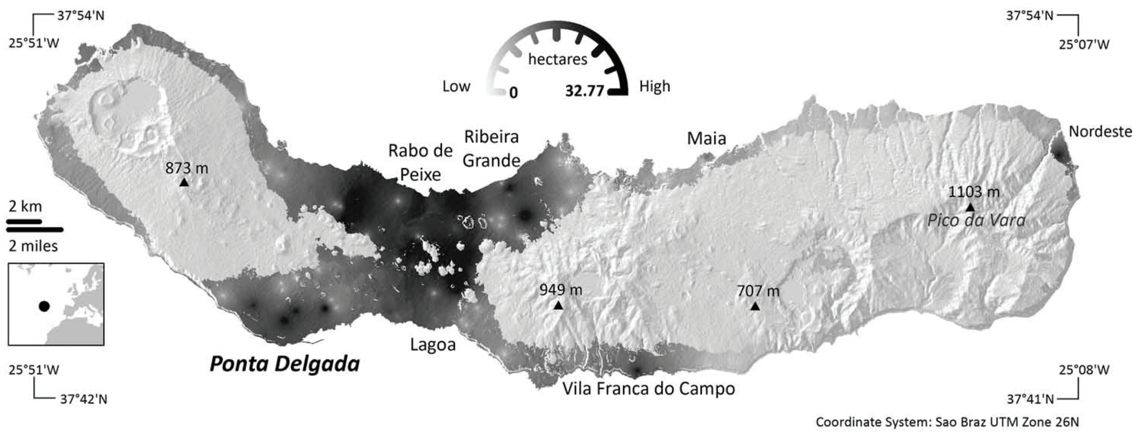

Figure 2. São Miguel's land development pressure during the 1990–2006 period.

Figure 3. Madeira's land development pressure during the 1990–2006 period.

the other hand, it is possible that a different interpolation algorithm (e.g., Kringing, Spline) could yield smoother interpolated surfaces whilst keeping RMSE low. Nonetheless, it was beyond the scope of this study to do a comparison of spatial interpolation methods. Therefore, to constrain RMSE values, an IDW interpolation has the drawback of producing the "bull's eye" effect. However, this drawback also proved to be helpful because the darker "bull's eye" acts as a hotspot of land development pressure, displayed in black in the figures. In this regard, the influence of the islands' settlements on the surrounding landscape can be appreciated by examining the gradient's intensity across the surfaces. Resorting to a gradient allows for an easy comparison of results, whereas "classification breaks are not comparable with other places and would be inappropriate for comparative studies" (Varanka 2010, 300).

A crucial finding in the results is that, as shown in the figures, during the 1990–2006 time frame, land development pressure had occurred not only in the vicinity of the main cities but also in smaller settlements. This indicates that there were strong LULC driving forces acting on the islands' landscape not related to major settlements, namely tourism activity. Therefore,

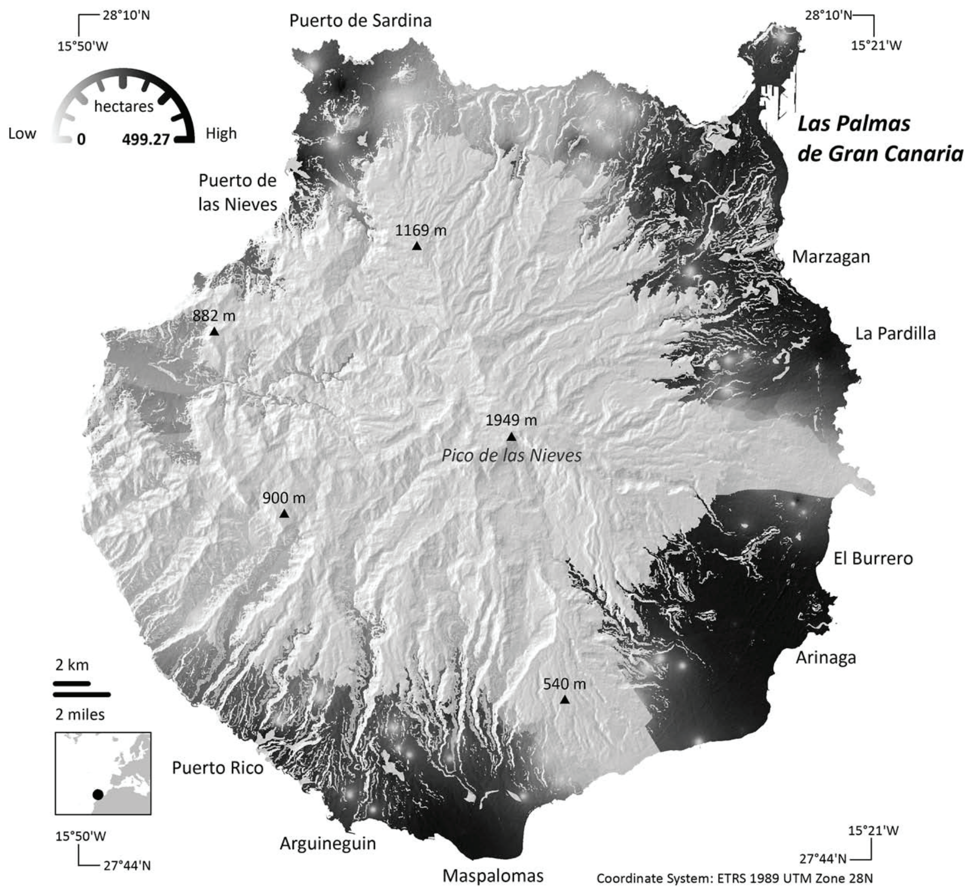

Figure 4. Gran Canaria's land development pressure during the 1990–2006 period.

results indicate that there are settlements in these islands that were responsible for more land development pressure than the island's main city, labeled in bold italic type. This process was particularly noticeable in the Spanish islands of Gran Canaria and Tenerife.

As shown in Figure 2, in São Miguel, land development pressure during 1990–2006 was higher in the northern central section of the island. Nonetheless, the island had the lowest gradient among the study areas, reaching a maximum of 32.77 ha of land development pressure during the 1990–2006 period. Because it is the least populous island among the study areas (0.14 M inhabitants), a relatively low land development pressure was expected. Moreover, an unstable climate averaging about 1000 mm (39.4 inches) of rainfall per year, and increased distance from Europe's mainland avoided São Miguel from becoming a mass tourism destination. São Miguel's foremost area of land development pressure had developed along the Lagoa–Rabo de Peixe/Ribeira Grande corridor (Figure 2).

In Madeira (Figure 3), land development pressure during 1990–2006 was higher in the south. The gradient shows that pressure was concentrated along the south and southeastern coast. In Madeira, between 1990 and 2006, a major area of land development pressure had developed along the Ribeira Brava–Machico corridor, encompassing the entire coastal southeastern region. Along this corridor, land development pressure had reached a maximum of 144.65 ha. Furthermore, Madeira was the best example among the case studies where its main city (Funchal, 0.11 M inhabitants) was associated to a hotspot of land development pressure. Over the years, tourism activity remained located in the city of Funchal, since there has been no resort development elsewhere in the island.

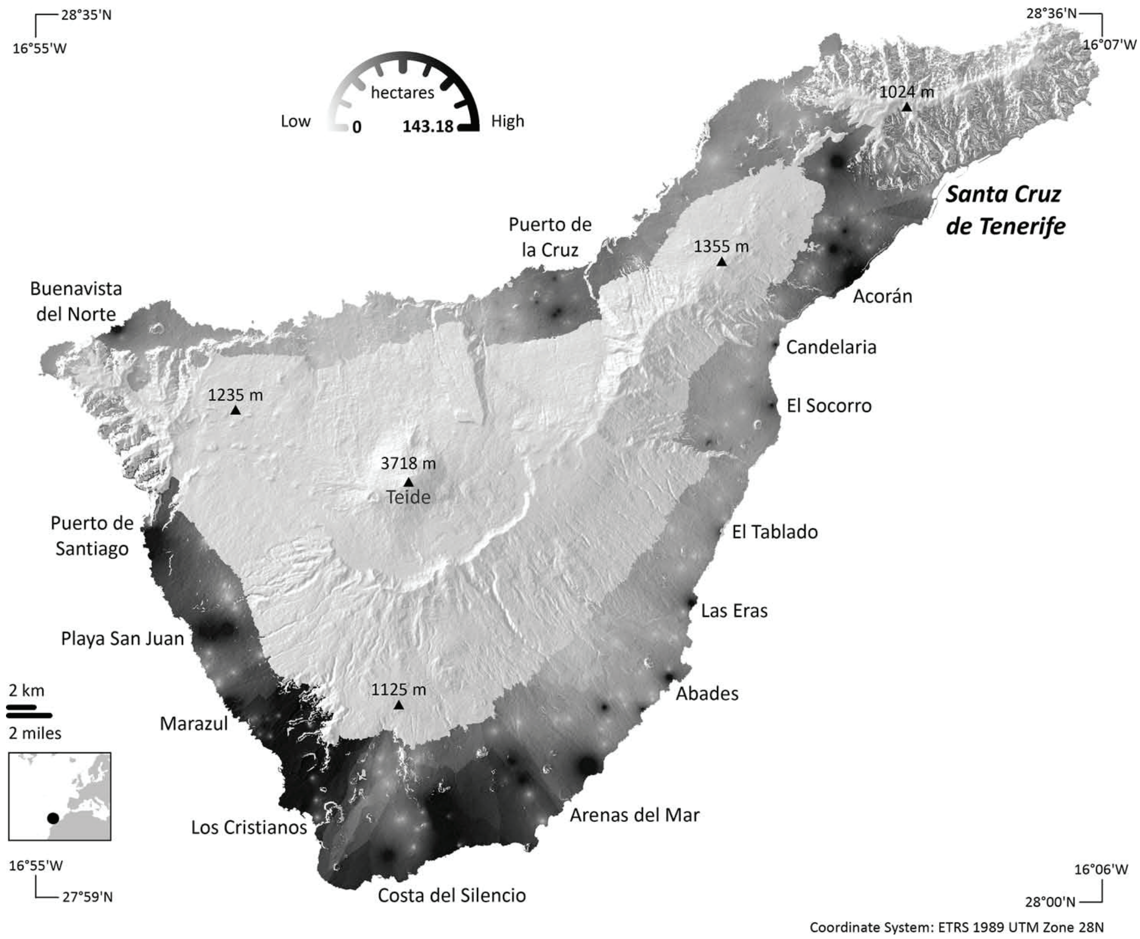

Figure 5. Tenerife's land development pressure during the 1990–2006 period.

As shown in Figure 4, the southeastern region of Gran Canaria is marked by land development pressure across the area surrounding Arinaga. The intense artificial land change that has occurred in this region stands out. Consequently, the gradient of land development pressure reached 499.27 ha, the highest, by far, among the study areas. Although the Arinaga industrial area was created in the mid-1970s, the 1990s saw a significant expansion. As shown, this has been recorded in Gran Canaria's land-change data. Another hotspot stands out in the south of the island surrounding Maspalomas, a tourist town. As such, the artificial land change occurring across this area mainly focused on tourism-related activities.

Finally, Tenerife (Figure 5) is the best example where the main city (Santa Cruz de Tenerife, 0.2 M inhabitants) was not associated with a hotspot of land development pressure. As shown in Figure 5, the south and southwestern sectors stand out as they had the main hotspots of land development pressure. Once again, empirical knowledge of the island's landscape associates this pressure to tourism development and associated infrastructures. In Tenerife, tourism-related activities predominately converged in the south along the high-pressure areas of Figure 5. On this matter, research has confirmed the relevance of economic activity among LULC driving forces. A recent study (Cunningham et al. 2015) examined the change from undeveloped to developed land use during the real-estate bubble and subsequent bust in Massachusetts, USA. Findings from Cunningham et al. (2015) show that land development spatial patterns can be associated with economic cycles. It is important to note that the 1990–2006 period discussed in the present study was marked by rapid increases in real-estate valuations. This real-estate bubble ended with the financial crisis of 2007–2008.

To contextualize the results, it is important to note that over the last few decades, artificial land change has been the main consequence of the islands' LULC driving forces. This increase in built-up areas has consolidated the cities. However, as the results show, it has mainly contributed to the growth of smaller settlements. To different degrees and extent, tourism-related infrastructures and improvements in road network are the main land-change driving forces in these archipelagos. Across the islands, tourism development and associated infrastructures became predominately located in the warm, clear, and dry leeward southern sides of the islands. Whereas, the visible land development pressure spreading inland is due to a continued improvement in road accessibility. This is associated with strong investment in road infrastructures in the islands, following the 1986 accession of Spain and Portugal to structural and cohesion EU funds. This led to major improvements in the islands' road network and a decrease in travel times. This investment allowed the built-up expansion of areas further inland, some of which were inaccessible before due to the huge costs of building new road infrastructures in these rugged volcanic islands.

5. Conclusions

No standard method exists for quantifying, measuring, and evaluating land development pressure. The method outlined in this article has been successful in rescaling through an IDW interpolation, coarse land-change-derived data into a higher resolution surface of land development pressure. This surface was interpolated, assuming that land development pressure is the magnitude of a landscape's artificial land change and that this magnitude can be represented with a gradient. The novel approach sampled ancillary data, taking into account a topographic resistance factor. IDW interpolation used this sampled ancillary information to double the data locations, confine the interpolation values, and assist the rescaling process.

Several advantages are immediately apparent from the method. (1) Data relies solely on land-use/land-cover datasets and a DEM, both available on public domain, allowing a seamless application of the method to other regions. (2) The method does not present a classification of land development pressure because the gradient of the pressure (hectares) is dependent on the observed size of artificial land-change areal units. Avoiding classification breaks and resorting to a gradient allows an easy comparison of results among distinct landscapes. (3) Rescaling the interpolated surface to a higher spatial resolution creates a visualization of the magnitude of land development pressure within the islands and its spatial variability across the landscape. On the other hand, the proposed method has some noticeable drawbacks. (1) Although encompassing large geographical extents, the method has been applied to coarse scale data and a relatively small dataset of sample points. Further testing is needed to assess the application's performance on higher resolutions and larger datasets. (2) The method was devised using volcanic islands as study areas. Therefore, it has to be calibrated before being applied to homogenous landscapes, where topography may not play a key role.

Overall, the method allows a spatially explicit representation of observed land development pressure. The modeled surfaces should be considered as a means for further studies of land-change driving forces rather than an end in itself. Therefore, as shown, the proposed method may be a valuable asset for identifying the interactions and spatial determinants involving anthropogenic land change.

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4.6. #5 Article

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A SPATIAL TYPOLOGY FOR SETTLEMENT PATTERN ANALYSIS IN SMALL ISLANDS

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ABSTRACT

This paper presents a method of settlement mapping and typological classification in small islands. Selecting the Atlantic islands of São Miguel, Madeira, Gran Canaria and Tenerife as study areas, data acquisition was made through classification of remotely sensed imagery. This study addresses the islands' lack of large scale spatial data, since there are no land use/cover datasets covering all these islands at a suitable scale for more detailed studies. Due to the large scale data produced, settlement differentiation is only possible through a morphological approach, therefore a morphological restricted typology is proposed. In order to apply the proposed settlement typology in a systematic and representative analysis, the study concludes measuring the relationship between settlement types and terrain attributes through a multinomial logit model. Overall, the study contributes to a better understanding of the islands' settlement pattern using a method that may be applied elsewhere.

Key words: built-up areas; settlement pattern; spatial typology; logistic regression; islands.

TIPOLOGÍA ESPACIAL PARA ANÁLISIS DE PATRONES DE ASENTAMIENTO EN ISLAS PEQUEÑAS

RESUMEN

En este artículo se presenta una metodología para cartografiar y clasificar asentamientos en islas pequeñas. Se utilizan como áreas de estudio las islas de São Miguel, Madeira, Gran Canaria y Tenerife. Dado que no existen datos de cobertura/uso del suelo que cubran estas cuatro islas a una escala adecuada para realizar estudios detallados, se generó una base de datos homogénea a partir de la clasificación de imágenes. Debido a la escala de los datos generados, la diferenciación de los asentamientos sólo es posible a través de un enfoque morfológico y, consecuentemente, la tipología

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propuesta es puramente morfológica. Con el fin de demostrar la aplicación de la tipología propuesta, el estudio concluye midiendo la relación entre los tipos de asentamientos y los atributos del terreno a través de un modelo de regresión logística multinomial. El interés del trabajo no es solo local (los resultados del estudio contribuyen a una mejor comprensión de las pautas de asentamiento en las islas analizadas), sino también metodológico, ya que la metodología desarrollada puede ser aplicada en otros lugares.

Palabras clave: área construida; patrones de asentamiento; tipología espacial; regresión logística; islas.

1. Introduction

Cartographic representations of settlements are useful for many study fields. Nonetheless, it is not straightforward to spatially define a settlement. According to the United Nations, "*settlement means the totality of the human community - whether city, town or village – with all the social, material, organizational, spiritual and cultural elements that sustain it*" (UN-HABITAT, 1976). Conceptually, this is one established definition for a settlement, but how does this translate spatially? In fact, the issues associated with the spatial delimitation of settlements are known in view of the increasing fragmentation of the built-up tissue, due to extensive urbanization provided by the generalization of private transport (Hasse & Lathrop, 2003; Williams, 2005). Moreover, while the main core is relatively straightforward to identify, the outlying areas are more complex to highlight in result of the scattered and diffuse built-up tissue. This paper seeks to address these issues, mapping settlements at a large scale for four Atlantic islands: São Miguel, Madeira, Gran Canaria and Tenerife.

In this paper a method is proposed to extract continuous built-up areas intended to represent settlements, labelling them as "Morphological Settlement Areas" (MSAs). Built-up area extraction was based on an automatic classification, followed by image interpretation of orthophotos. In spatial terms, this study assumes as "built-up area" a homogeneous landscape unit consistent with artificial land cover characteristics that distinguish it from the surrounding landscape. The study's focus is on built-up areas, rather than urban areas, since the definition of the latter implies additional knowledge about human land use (Comber, 2008).

Afterwards a method is proposed of settlement classification in a fourfold spatial typology. An attempt will be made to indicate some problems with settlement typologies and one will be suggested. The goal of the proposed settlement typology is to contribute to the systematic and representative analysis of settlements. This proposed morphological settlement typology will be applied to the empirical reality of the four islands, classifying the MSAs. Although resorting to four islands as study areas, the method's low data requirements (only remote sensing datasets are used) make mapping and classification of settlements easily replicable in other small islands, assuming as "small", islands with less than 3,000 km^2.

Rodrigues, M. (2015): "A spatial typology for settlement pattern analysis in small islands", GeoFocus, nº15, p. 3-26. ISSN: 1578-5157

This study innovates proposing a morphological restricted settlement typology, followed by the application of a multinomial logit model (MLM) to the proposed settlement typology. In order to apply the proposed settlement typology in a systematic and representative analysis, this study uses the MLM to measure the relationship between settlement types and terrain attributes, serving as an example of the application of the proposed settlement typology and laying the foundation for further studies. The MNL has a potential wider application to small volcanic islands, where the physical landscape has a pivotal role.

Following the study's aims, the research problem addresses the islands' lack of large scale spatial data. The only available land use/cover data covering all the studied islands are the CORINE datasets, which have a limited application due to scale constrains. Therefore, there are no land use/cover datasets covering all these islands at a suitable scale for more detailed studies. On the other hand, settlement differentiation with the large scale data produced is only possible through a morphological approach; hence, a settlement typology was defined with an exclusively morphological criterion.

2. Literature review

The most commonly criteria for the spatial delimitation of settlements can be grouped into three broad categories: 1) homogeneity, on the basis of which spatial units can be grouped within parameters of minimum statistical variation of simple indicators (EUROSTAT, 2012); 2) functional, on the basis of which spatial units are grouped among those that have intense exchanges of people, goods or communication flows (ESPON, 2005); 3) morphological, according to which one can define a spatial continuum through land cover patterns (Weber, 2001; Ackermann *et al*., 2003). In all this criteria, typical difficulties encountered stem from the spatial heterogeneity of settlement patterns and non-uniform availability of data.

The European Spatial Planning Observatory Network (ESPON) was founded by the member states of the European Union (EU) in 2002 in order to improve the European spatial development policy (EUROSTAT, 2012). The establishment of ESPON have increased the interest in comparative settlements studies among member states. In their effort, ESPON (2005) has produced a list of "Functional Urban Areas" for 29 European countries. A "Functional Urban Area", as defined by ESPON, consists of a cluster of municipalities and commuting area. In 2007 this method was enhanced to incorporate the "Morphological Urban Areas", contiguous municipalities with thresholds of population density. Although ESPON continues to have a major impact in trans-national studies of settlements among EU states, their scope is aimed at national scales. Issues arise at a large scale delimitation of settlements, since administrative units are not sufficiently disaggregated, and on the other hand, at these scales, it is often impossible to employ the functional criterion due to lack of data. As such, only the morphological criterion suits a large scale study, namely through patterns of land use/cover.

The morphological criterion for the delimitation of settlements integrates particularly well with Remote Sensing (RS) methods, namely to extract built-up areas from high resolution imagery.

Rodrigues, M. (2015): "A spatial typology for settlement pattern analysis in small islands", GeoFocus, nº15, p. 3-26. ISSN: 1578-5157

Deriving information from RS can be done through a collection of digital analysis techniques, such as image interpretation, image classification, image transformation, and change detection (Yang, 2010). A considerable amount of literature has been published on RS methods and these have been extensively applied in several studies (Hall, 2010). Because of their cost effectiveness and temporal frequency, RS approaches are widely used for the acquisition of detailed and accurate land surface information and monitoring changes at regular time intervals (Sharma *et al*., 2012). However, production of spatially detailed and thematically accurate information from imagery continues to be a challenge (Jensen & Im, 2007). This is due to the heterogeneous nature of landscapes, which makes discriminating land cover classes' difficult (Barnsley *et al*., 1993). This field of study has attracted the attention of many researchers and several studies have been conducted using different image classification algorithms (Blaschke *et al*., 2004; Lu & Weng, 2007; Sharma *et al*., 2012).

Nonetheless, once a suitable dataset of land cover is gathered, it is necessary to apply criteria in order to identify settlements from land cover patterns. As Gluch & Ridd (2010) highlight, the "*determination of the composition of a single pixel is usually of little value in and of itself*". It is the aggregation of multiple adjacent pixels of similar composition that make analysis possible, namely the built space continuum. Several spatial delimitation of settlements are based on the criterion of built space continuity (Weber, 2001; Ackermann *et al*., 2003) and the definition proposed by the United Nations (UN), that a settlement is a contiguous built-up area with a maximum of 200 meters between building structures (NUREC, 1994). The publication of the Atlas of agglomerations in the EU by NUREC in 1994 is an important milestone. Employing the definition of built space continuum proposed by the UN, this atlas was prepared with information about the population and area of more than 300 EU settlements. A more recent example is the "Urban Morphological Zones" (UMZs) datasets. UMZs are European Environmental Agency datasets, built with land cover classes used to identify the physical boundaries of urban settlements at a 1:100,000 scale. According to the EEA (2006), an UMZ can be defined as an agglomerated set of urban areas laying less than 200 m apart. If the considered urban patches are closer than 200 m, they are merged together through object segmentation to make a larger individual urban area: an UMZ representing an urban settlement.

Object segmentation is a dominant method in academic literature to analyse built space continuity, namely through shape-based and texture measures (Benediktsson *et al*., 2003; Blaschke *et al*., 2004; Liu, *et al*., 2007; Aytekin & Ulusoy, 2011). In this field of study the shape-based method of mathematical morphology (MM) has proven to perform particularly well over RS images (Jin & Davis, 2005; Liu *et al*., 2007; Pesaresi & Ehrlich, 2009). Mapping spatial patterns with morphological image processing is typically used in forest and biodiversity studies, in the field of landscape ecology. Vogt *et al*. (2007) and Soille & Vogt (2009) have recently developed a morphological image processing method for land-cover patterns. In the present study, this same method was applied to built-up areas to obtain settlements.

Once we have a cartographic database with the delimitation of settlements, in order to develop a systemic and representative analysis, it is necessary to use typologies. A settlement typology can be seen as a process which analyses and interprets the various characteristics of settlements to provide a classification. The typology also becomes a toolkit which informs further

Rodrigues, M. (2015): "A spatial typology for settlement pattern analysis in small islands", GeoFocus, nº15, p. 3-26. ISSN: 1578-5157

study and interpretation of settlements and their characteristics, including setting up and selecting categories to organise and analyse new data (Newman *et al*., 2008). Settlement typologies can be grouped in four broad categories: 1) Dimensional typologies, where the typological adopted criteria are primarily related to some quantitative variable, e.g. number of inhabitants (Mitković *et al*., 2002), this is the category of typological studies most frequently represented in the literature; 2) Spatial typologies, where the typological criteria are concerned with spatial attributes of settlements (Lamovšek, 2007), such typologies tend to include criteria related to settlement morphology and/or patterns of spatial distribution of population; 3) Functional typologies, where settlements are classified on the basis of functional data (Alvheim, 2000); and finally, 4) Multidimensional typologies approaches, that pair together two or more typology criteria (Coombes, 2004). Typologies of this kind are rather rare, owing to high data requirements.

In Europe, large scale comparative empirical studies are difficult due to incompatible statistical data. EUROSTAT (the statistical office of the EU) publishes mainly national and regional information. Difficulties arise when an attempt is made to implement settlement typologies in a wider application apart from academic study cases, since access to quantitative and qualitative data becomes a major problem in the formation of a typology (Newman *et al*., 2008). Thus, the proposal of a settlement typology presents a series of problems. Perhaps the most important one is that classification thresholds are not always consistent, moreover, a more inclusive perspective highlights that due to non-uniform availability of data, these cannot be realistically used within the planning and management process. Even considering there is available data among distinct regions, it is often impossible to use the same thresholds in order to classify the settlements. Hence, only spatial typologies can be useful to analyse different regions, since they do not rely on socio-economic variables. Nevertheless, spatial typologies do rely on spatial data sources with the mapping of settlements.

Once a typology is set, it can serve as basis for further analysis, setting up categories to organise and analyse new data (Newman *et al*., 2008). In order to apply the proposed settlement typology in a systematic and representative analysis, this study concludes measuring the relationship between settlement types and terrain attributes through a multinomial logit model, with the proposed settlement typology serving as a dependant variable. In spatial analysis, logistic regression is used to predict probabilities for the presence or the absence of a specific geographic characteristic (Triantakonstantis *et al*., 2011), deriving relationships between observed spatial data (the dependent variable) and the values of physical, economic or social indicators (the predictive variables) (Millington *et al*., 2007). This same method has been used to model urban growth (Hu & Lo, 2007), predict urban-rural land conversion (Huang *et al*., 2009) or broader land use/cover change (Millington *et al*., 2007). Here it will be used to analyse the relationship between settlement types and terrain attributes, as an assumed reductionist approach. Recent studies (Millington *et al*., 2007; Wang & Kockelman, 2009; Huang *et al*., 2009) have modelled the relationship between explanatory (predictive) and response variables in spatial analysis. The multinomial logistic regression model is used when the dependent variable has more than two nominal categories. It is flexible enough to be tailored to individual landscapes and it is available from most statistical packages.

Rodrigues, M. (2015): "A spatial typology for settlement pattern analysis in small islands", GeoFocus, nº15, p. 3-26. ISSN: 1578-5157

3. Study area and data sources

As study areas, the most populous islands in the outermost regions of Portugal and Spain were selected: São Miguel, Madeira, Tenerife and Gran Canaria. These islands make part of the *Macaronesia* ecoregion and are all volcanic in their origin. Tourism development and associated commercial and residential growth dramatically changed the landscape of these islands in the last decades. Although having a recent settlement pattern and much less comprehensive public transport than old settled regions (e.g., railroad transportation have never existed), human settlement is extremely conditioned by the physical geography of the islands and, as such, there is much less sprawl in comparison with other newly settled regions.

São Miguel is the largest and most populous island in the Portuguese Azores archipelago. Covering 759 km^2, the island has approximately 140,000 inhabitants. Madeira is the largest island of the Portuguese archipelago with the same name. It has an area of 741 km^2 and approximately 260,000 inhabitants. Together these two islands comprise more than 75% of the total population of the two Portuguese outermost regions. Gran Canaria is the second most populous island of the Canary Islands, with approximately 850,000 inhabitants. Gran Canaria's surface area is 1,560 km^2. Tenerife is the largest and most populous of the Canary Islands, with a surface area of 2,034 km^2 and approximately 908,000 inhabitants. These two islands comprise more than 80% of the total population of this Spanish outermost region.

Due to the complexity of built-up areas, several studies have shown that high spatial resolution imageries are required in artificial environment analysis (Jensen & Cowen, 1999; Blaschke *et al*., 2004). As such, orthophotos (georeferenced and geocorrected aerial images) at a 0.5 meter resolution were obtained from the "Instituto Geográfico Português" and "Cartográfica de Canarias", the public companies responsible for geographic information production in these islands. The acquisition dates are as follows: São Miguel: 2006; Madeira: 2006; Tenerife: 2008; Gran Canaria: 2008. The study data source consisted in a generalization of the islands RGB ortophotos to a 5m pixel, accomplished using a nearest neighbour resample. Afterwards images were mosaicked in order to obtain a single file for each island. Since the study was intended to focus on extended geographical areas (4 islands), a 5m spatial resolution was selected. A viable resolution to accommodate the data processing had to be used and, on the other hand, there is literature consensus that a 5m resolution is sufficient for the identification of built-up areas (Jensen & Cowen, 1999). In order to apply the multinomial logistic model, a set of physical data was directly computed from the 30 meter resolution grids of the "ASTER Global Digital Elevation Model Version 2": 1) Altitude (meters); 2) Aspect (degrees); 3) Distance to coastline (meters) and 4) Slope (degrees).

Rodrigues, M. (2015): "A spatial typology for settlement pattern analysis in small islands", GeoFocus, nº15, p. 3-26. ISSN: 1578-5157

4. Methods

4.1. Mapping and classification of settlements

4.1.1. Built-up area extraction

A decision was made to apply a simple and fast classification method; an unsupervised classification, which has the disadvantage of overestimating the classified areas (Epstein *et al*., 2002). Nonetheless, poorly corrected areas may be corrected through image interpretation. Yang (2010) identified several advantages of image interpretation and ways it can be incorporated effectively into a digital classification procedure with the use of on-screen digitizing, multiple zooming and other GIS tools, such as overlaying and recoding.

In an unsupervised classification, heuristic processes are usually used (Corander *et al*., 2009). One of the most widely used heuristic methods is the iterative optimization of clusters, also known as K-means. K-means unsupervised classification uses a cluster analysis that relies on the choice of a number of classes to partition an n-dimensional imagery into *k* exclusive clusters, which are then filled in an iterative process according to their radiance values (Cihlar *et al*., 2000). Since its performance strongly depends on the initial estimation of the partition, a relatively large number of clusters are generally recommended (Cihlar *et al*., 2000). Thus in this study, in order to achieve a binary classification (built-up/non built-up), 50 initial classes were selected and data was assigned to homogenous classes based on spectral properties.

The identified built-up patches were made by pixels completely occupied by any artificial human constructions. Therefore these initial areas do not aim to include vegetated pixels, even if these are part of the urban structure, as is the case of urban parks and gardens, or any kind of bare soil that is not developed. Thus, the results initially classify all impervious soil and do not make any criterion for land use or occupation.

The 50 classes raster was then reclassified in order to leave considered built-up classes with a single value (e.g., 1) and the remaining classes with another value (e.g., 0), thus creating a binary raster: built-up and non-built-up. The reclassification procedure had to be done island-by-island, visually identifying the classes that best corresponded to built-up areas. As expected, this type of classification originates an overestimation of the built-up areas. As such, image interpretation, by means of editing classification errors using on screen recoding, was employed. Therefore, in order to standardize the methodology and reduce analysis time, making it easily applicable to other regions, it was decided that the best method to adopt for this study was an automatic unsupervised classification followed by image interpretation. A crucial aspect of the methodology had to be done during image interpretation. This consisted in deleting road features to insure that built-up patches were not connected via road network, otherwise built-up patches would become merged and even isolated patches would be agglutinated into one single patch, because of connecting linear features,

Rodrigues, M. (2015): "A spatial typology for settlement pattern analysis in small islands", GeoFocus, nº15, p. 3-26. ISSN: 1578-5157

rendering impossible the identification of individual settlements. As such, this method may not suit all types of analysis.

4.1.2. Morphological settlement areas

NUREC (1994) produced the Atlas of agglomerations in the European Union based on a simple common denominator (i.e., the UN criterion of a maximum of 200m between building structures to delimit a settlement). More recently EEA (2006) applied the same criterion over land cover data to derive UMZs. Nonetheless, NUREC and EEA methods were aimed at a small scale in view of the administrative units. At a large scale study, the 200m criterion would excessively extend the size of the agglomerations and, as a result, many settlements would cover a too large proportion of land according to their true size. This would also trigger the agglutination of distinct settlements. As such, in this large scale study the applied distance criterion was lower, but at the same time, flexible enough to be applicable to different data sources as needed.

Based on the NUREC (1994) and EEA (2006) methods, this study definition of a "Morphological Settlement Area" (MSA) is a set of built-up patches lying less than 30m apart. The present study also relies closely on Vogt *et al*. (2007) and Soille & Vogt (2009) methods and their use of morphological image processing as an approach for mapping land-cover patterns.

The choice of aggregating all the features at 30 meters, relates to the fact that the spatial resolution of the most widely available imagery data source in these islands (i.e., LANDSAT images) is 30m. As such, although employing high resolution datasets in this study (5 meters), this method has been developed to be applied to other imagery data sources. For LANDSAT images, the 30 meters spatial resolution of imposes this as the minimum to aggregate the built-up patches.

To obtain continuous built-up areas identifying settlements, the binary image resulting from the previous built-up extraction was transformed recurring to mathematical morphology (MM). The role of MM is to improve the segmentation of image structural components. MM operates on two sets: the first one is the image and the second one is the structuring element (Benediktsson *et al.*, 2003). In this application the structuring element used was a 6x6 matrix, since the spatial resolution of the data was 5m and a two-step process of dilation and erosion of the binary image cells by 30m was undertaken. The fundamental operators in mathematical morphology are dilation and erosion (Benediktsson *et al.*, 2003). Since MM is well established as a method and used in several studies, only a verbal description of the algorithms will be provided (see Soille, 2003 for a formal mathematical introduction). Data processing was done with the freeware software GUIDOS, which implements the raster-based classification algorithm by Soille & Vogt (2009).

In figure 1, let foreground pixels be represented by logical 1's (built-up area) and background pixels by logical 0's (non-built-up area). The basic effect of dilation on binary images is to enlarge the areas of foreground pixels at their borders. The areas of foreground pixels thus grow in size while the background, among and within them, shrink. Taking a 6x6 matrix for the structuring element with the centre pixel used as the origin of the set B, then figure 1 highlights the

Rodrigues, M. (2015): "A spatial typology for settlement pattern analysis in small islands", GeoFocus, nº15, p. 3-26. ISSN: 1578-5157

dilation process. If the pixel is set to foreground (built-up), it remains such. If the pixel is set to background (non-built-up), but at least one of its eight neighbours (connectivity in cardinal directions) is set to foreground (built-up), the pixel is converted to foreground (built-up). If the pixel is set to background (non-built-up) and none of its eight neighbours (connectivity in cardinal directions) is set to foreground (built-up), the pixel remains set to background (non-built-up).

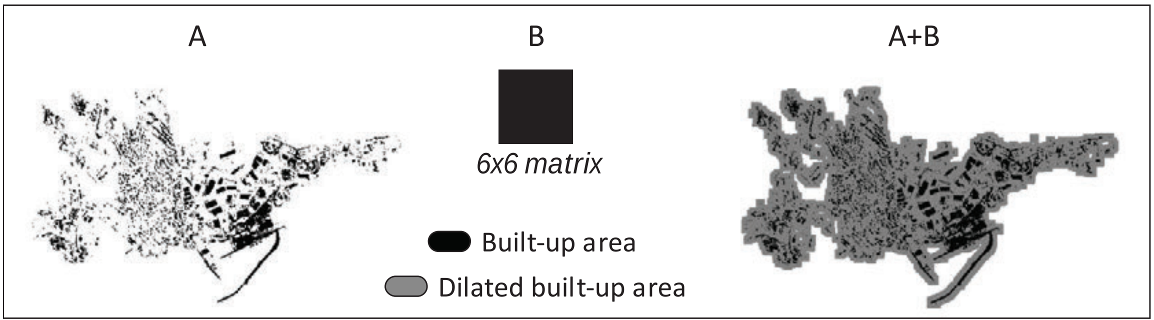

Figure 1. Dilation process

After the dilation process all built-up patches laying 30 meters apart are aggregated into single continuous surfaces. The next step consists in making these surfaces to recede on their edges, in order to maintain settlements as accurate as possible. The boundaries of the surfaces can be receded using another MM operator: erosion. The basic effect of erosion on a binary image is to erode away the boundaries of foreground pixels. Thus areas of foreground (built-up) pixels shrink in size and non-built-up areas among and within those areas become larger.

Once again the 6x6 matrix of logical 1's, with the middle point chosen as the origin of the set, is used as the structuring element B (figure 2). To compute the erosion of a binary input image by this structuring element, each of the foreground pixels in the input image were considered in turn. For each input pixel, the structuring element is superimposed on top of the input image, so that the origin of the structuring element coincides with the input pixel coordinates. If the input pixel is set to foreground (built-up) and all its eight neighbours (connectivity in cardinal directions) are also set to foreground (built-up), then the pixel remains set to foreground (built-up). If the input pixel is set to foreground (built-up) but at least one of its eight neighbours (connectivity in cardinal directions) is not, the pixel is set to background (non-built-up). Input pixels set to background (non-built-up) remain such. The effect of this operation is to remove any foreground (built-up) pixel that is not completely surrounded by other foreground (built-up) pixels, assuming eight-cell connectedness (figure 2).

Taking one settlement as example, figure 3 compares the results obtained from the built-up area extraction (A) and after the dilation and erosion process (B), which created the final MSAs datasets. Essentially, the proposed MSAs are aggregated continuous surfaces of built-up tissue void of road-network; the absence of road network prevents having individual MSAs merged together via road features.

Rodrigues, M. (2015): "A spatial typology for settlement pattern analysis in small islands", GeoFocus, nº15, p. 3-26. ISSN: 1578-5157

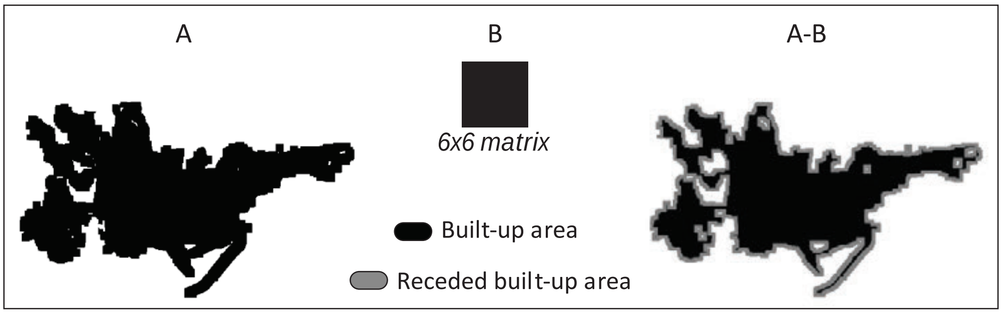

Figure 2. Erosion process

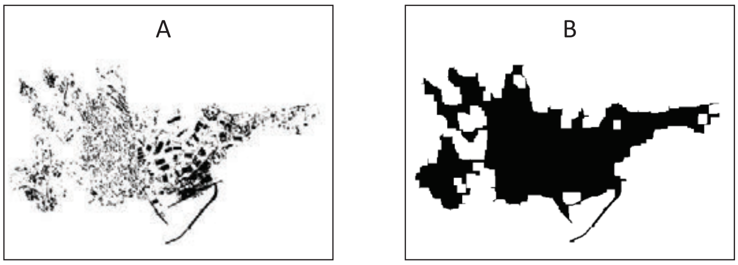

Figure 3. Built-up patches (A) and resulting morphological settlement area (B)

The resulting map from this process remained a binary map with cells representing MSAs coded as 1s. To individualize each MSA into a unique continuous area representing an individual settlement, cells coded as 1s belonging to the same contiguous area were grouped with a unique identifier. This was done confirming the connectivity between cells coded as 1s, testing if they were within the immediate four-cell neighbourhood (left, right, above, or below) of each other. If the connectivity spatial requirements were meted, cells coded as 1s were grouped into contiguous areas of cells. With each area having a unique value assigned to it, thus representing an individual settlement.

4.1.3. Accuracy assessment

The MSAs' accuracy assessment was performed individually for each island using a cross tabulation matrix. According to reference literature (Foody, 2002), the sample size was computed, aiming at an accuracy of 85%, at the 95% confidence level. An overall accuracy of 80-85% has often been cited as recommended target accuracy for land cover maps (Foody, 2002). The obtained 196 minimum sample size was rounded up to 200 sample points, which in turn were created recurring to a simple random sampling. Since only binary maps had to be assessed, a simple random sampling design was used. As such, in each island a random set of 200 points was created with image interpreted samples used as reference data. The 200 points were verified and labelled against the reference data, with built-up pixels being represented by logical 1's, and non-built-up pixels by logical 0's. Cross tabulation matrices were then designed to assess the quality of the MSAs' accuracy and accuracies statistics derived from the matrices.

4.1.4. Settlement typology

When developing this settlement typology two conditions had to be met: 1) the typology thresholds should be equally applied in all the studied islands; 2) in each island, 100% of the morphological settlement areas (MSAs) had to be classified. With these two conditions in mind, a settlement typology with four classes is proposed, on the basis of two morphological dimensions: size and proximity, with proximity being computed as the Euclidean distance from settlement edge to the closest settlement edge.

Main settlement: The main settlement corresponds to the largest settlement in the landscape (i.e., main settlement = largest patch area). In the case of the studied islands, the main settlement corresponds to the main city in each island.

Consolidated settlements: The consolidated settlements correspond to MSAs that make the primary settlement cores. They have high built-up densities, since these are settlements in which there is a close juxtaposition of built-up area. These settlements are characterized by being the largest settlements in the landscape, with their size resulting from having multiple built-up patches aggregated. Under the proposed settlement typology these areas are identified by having a MSA patch area greater than one standard deviation to the island mean, i.e., consolidated settlements = (MSA patch area > μ+1σ).

Fragmented settlements: These settlements are typically associated with patterns of clustered, non-traditional centres, which may arise through sprawling processes. They have lower built-up densities. These areas are associated with the expansion of built-up tissue and as such they are located, usually, in the vicinity of consolidated settlements. Under the proposed settlement typology, fragmented settlements correspond to MSAs with a patch size smaller than one standard deviation to the island mean and a patch proximity smaller than the island mean, i.e., fragmented settlements = (MSA patch size < (μ+1σ) AND MSA patch proximity < μ).

Dispersed settlements: Dispersed settlements are a typical pattern of rural landscape, resulting from isolated and small built-up areas not grouped into villages and hamlets. Sparsely located, dispersed settlements correspond, under the proposed settlement typology, to MSAs with a patch size smaller than one standard deviation to the island mean and a MSA patch proximity higher than the island mean, i.e., dispersed settlements = (MSA patch size < (μ+1σ) AND MSA patch proximity > μ).

4.2. Multinomial logit model

In order to have the same data resolution as the physical variables computed from the "ASTER Global Digital Elevation Model Version 2", the MSAs datasets were generalised using a

Rodrigues, M. (2015): "A spatial typology for settlement pattern analysis in small islands", GeoFocus, nº15, p. 3-26. ISSN: 1578-5157

nearest neighbour resample to a 30 meter pixel. A set of rather standard routines were followed to convert the raster maps to data matrices, with pixels being treated as cases. MSAs' typology was treated as the categorically distributed dependent variable, and altitude, slope, aspect and distance from the coastline, as predictors. Since the goal of the proposed settlement typology is to contribute to the systematic and representative analysis of settlements, this study assumes the variables as a shortened selection for the development of a simplified reductionist model, an example of an application using the proposed settlement typology. It is clear *a priori* that there are explanatory driving forces that are not represented in the variables.

Multinomial logistic regression was performed for each of the islands separately. The logit models were used to predict the probability of existence of each of the settlement types. Consequently, the value of the membership of each pixel (case) to a given typology class can be determined as a function of the values of the terrain attributes for that pixel (case). The lowest ratio of cases to independent variables was in Madeira, 17001.75 to 1 (table 1). Thus the requirement for a minimum ratio of cases to independent variables was by far satisfied. With a highest score of 0.092 (table 1), the models standard errors of coefficients indicate no numerical problems. The benchmark used to characterize the models as useful was the rate improvement over the accuracy achievable by chance alone (Costea & Eklund, 2003). "By chance accuracy" is computed by summing the squared percentage of cases in each class of the dependent variable. Since multinomial logistic regression is well established as a method used in several studies and available in several statistical software, only an analysis of the results will be provided (see Menard, 2002 for a formal mathematical introduction).

Table 1. Multinomial logit models

	S. Miguel	Madeira	G. Canaria	Tenerife
Ratio of cases to independent variables	17195.25	17001.75	27549.5	33847.75
Highest standard errors of coefficients	0.092	0.070	0.036	0.046
Accuracy achievable by chance alone	37.68%	31.86%	39.93%	35.07%

5. Results

5.1. Mapping and classification of settlements

The islands' settlement system dates back to colonization in the fifteenth and sixteenth centuries. Over the course of time, settlement has developed primarily along the more accessible areas on the coast and in a few interior plains. Due to the islands' volcanic nature, the coastal zone had a better agricultural capacity, lower altitude and greater ease of communication. In the case of São Miguel and Madeira, settlement have grown denser in the south (figure 4 and 5), while in Gran Canaria and Tenerife, it is the northeast that has the highest settlement density (figure 6 and 7). These were the areas with better agricultural capacity and existence of natural harbours. Nowadays, in all the cases, the areas of highest density correspond to major cities, mainly because of the natural attraction to urban centres and, on the other hand, due to the process of urbanization that has

Rodrigues, M. (2015): "A spatial typology for settlement pattern analysis in small islands", GeoFocus, nº15, p. 3-26. ISSN: 1578-5157

characterized these regions in the last decades. This process has been determined by forces of attraction and repulsion and driven primarily by economic motivations, associated with dynamics of growth and job creation. As such, these factors, paired with the islands' physical geography, contributed to an asymmetric spatial distribution of settlements.

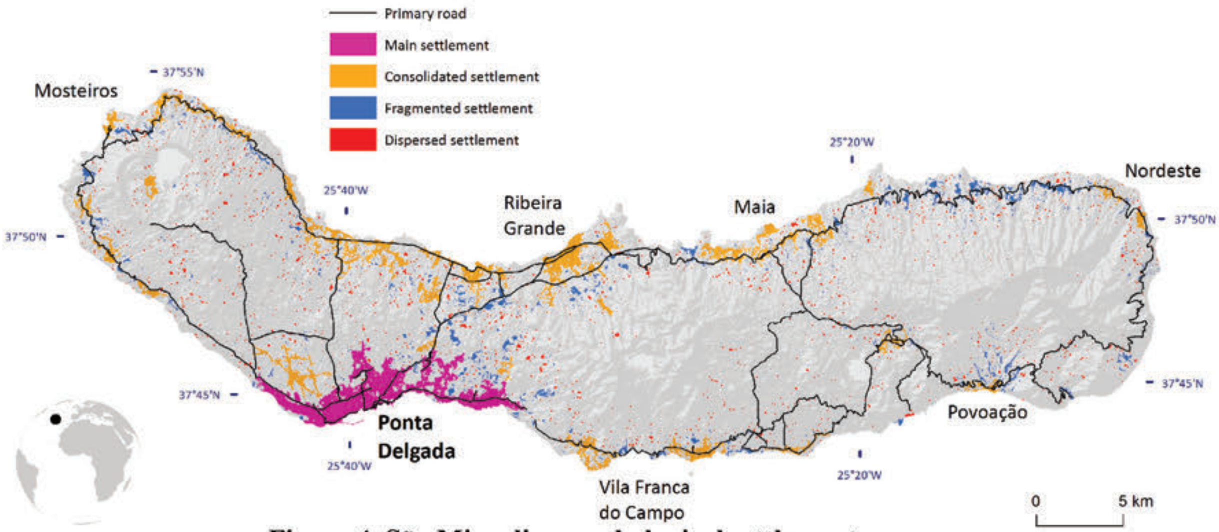

Figure 4. São Miguel's morphological settlement areas

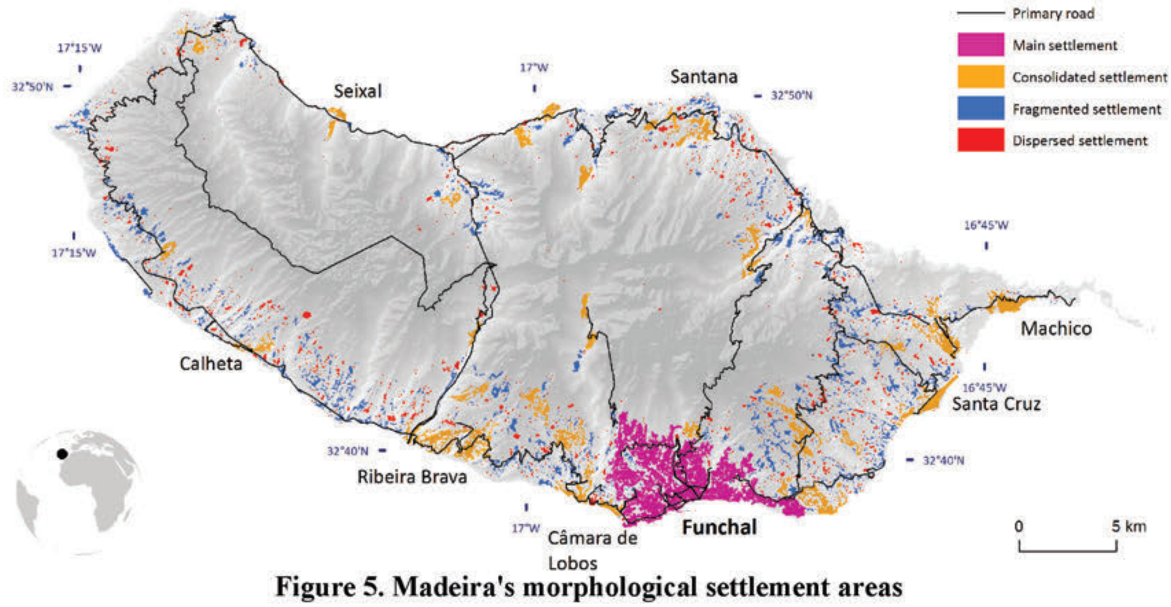

Figure 5. Madeira's morphological settlement areas

In Madeira there is a clear asymmetry between the north and south (figure 5). The northern slopes of the island are more windswept and rainy with high cliffs which end abruptly in the sea. The south slopes are more sunny, less rainy and warmer, the sea is calmer and there are good

Rodrigues, M. (2015): "A spatial typology for settlement pattern analysis in small islands", GeoFocus, nº15, p. 3-26. ISSN: 1578-5157

natural harbours which facilitated the initial settlements. Unlike the island of São Miguel, the interior has never been exploited for agriculture or livestock due to its very rugged topography. Figure 5 shows a large concentration of MSAs in the southeast of the island, as it relates to the location of primary urban centres and the existence of the main ports and the airport. The island has vast uninhabited areas in the interior which coincide with areas of rugged terrain, where settlements have concentrated at the mouths of the ravines.

Gran Canaria's MSAs are clustered around the capital (Las Palmas de Gran Canaria) and its adjacent municipalities in the northeast of the island, while inland and in the west, MSAs are rather sparse (figure 6).

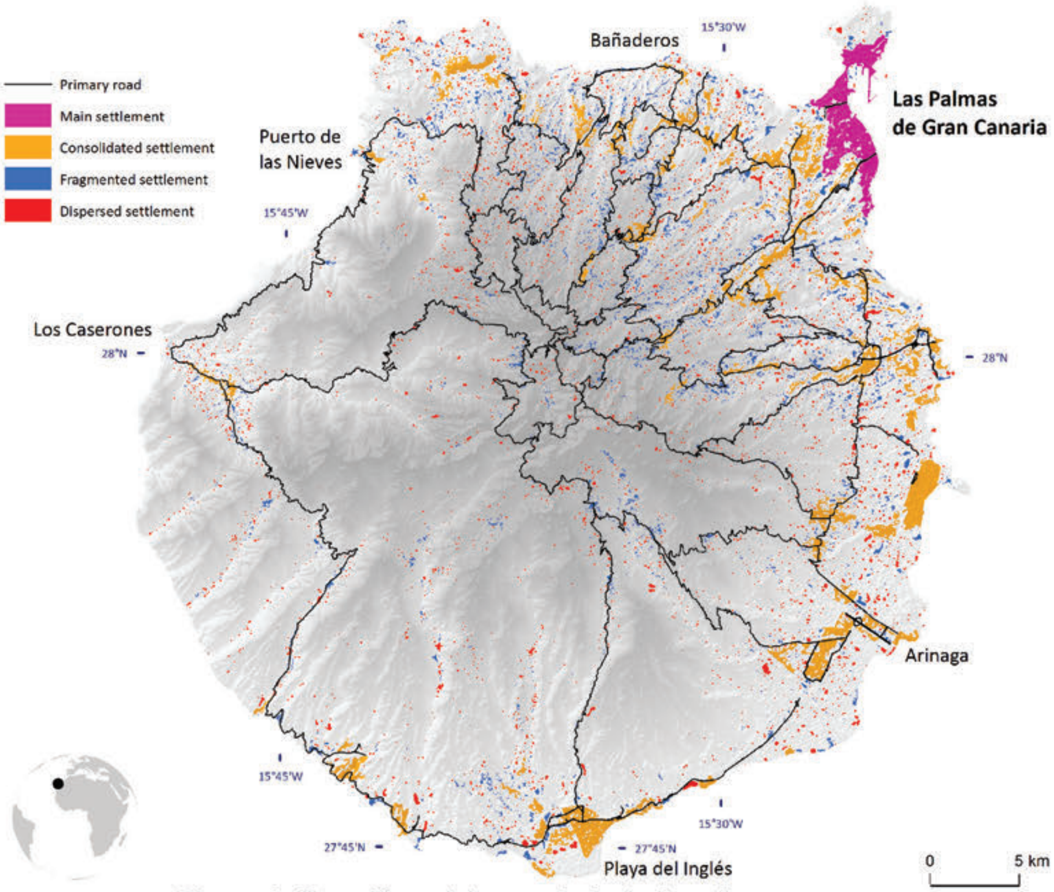

Figure 6. Gran Canaria's morphological settlement areas

In Tenerife, the cities of Santa Cruz de Tenerife and La Laguna San Cristóbal are physically linked through a conurbation making Santa Cruz de Tenerife a metropolitan area, island-wide (figure 7). There is also a marked contrast in Tenerife and Gran Canaria, between north and south, where in both cases the north has a higher settlement density. Nonetheless, in these Spanish islands

Rodrigues, M. (2015): "A spatial typology for settlement pattern analysis in small islands", GeoFocus, nº15, p. 3-26. ISSN: 1578-5157

the south started to attract more population due to resort development. As a matter of fact tourism was, and still is to some degree, a major pattern-forming force in these islands.

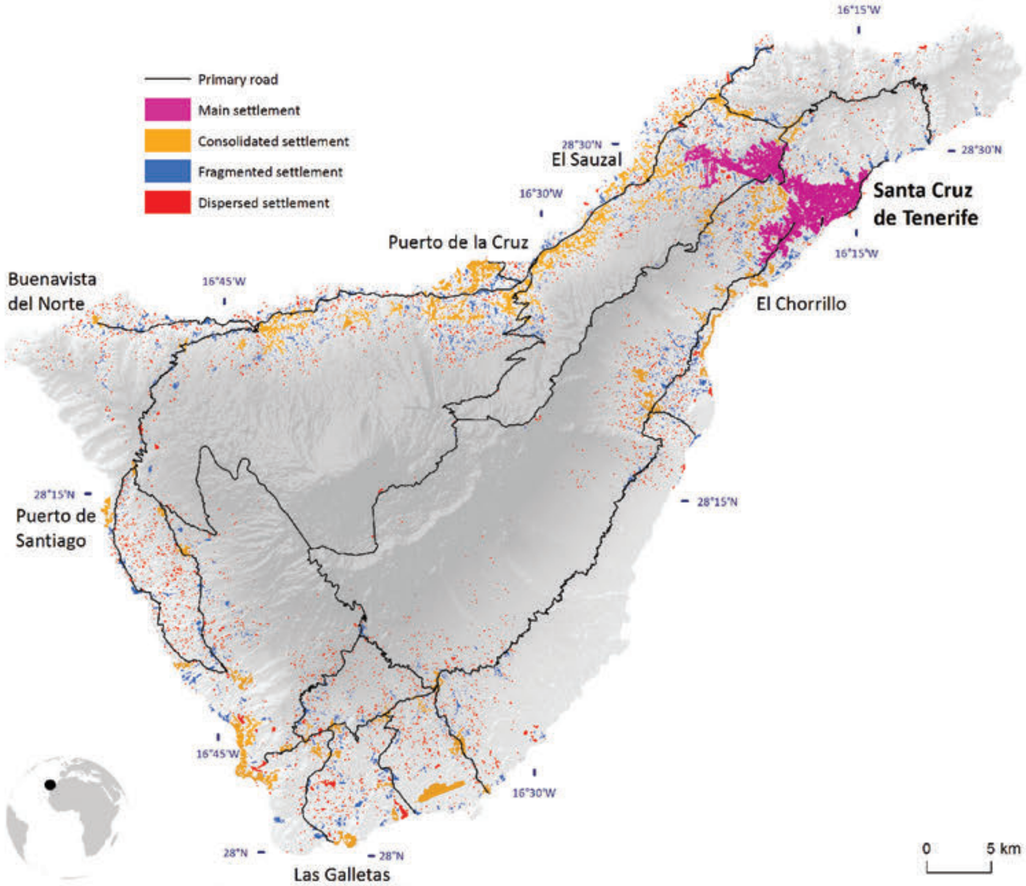

Figure 7. Tenerife's morphological settlement areas

5.1.3. Accuracy assessment

Table 2 presents the MSAs' accuracy assessment. Overall accuracy ignores the off-diagonal elements the omission and commission errors. Omission errors are a calculation of cases (cells) that have been incorrectly attributed to other classes; while commission errors are a calculation of cases (cells) which have been incorrectly included in the class.

Rodrigues, M. (2015): "A spatial typology for settlement pattern analysis in small islands", GeoFocus, nº15, p. 3-26. ISSN: 1578-5157

Table 2. MSAs' accuracy assessment

	Overall accuracy (%)	Errors of omission (%)		Errors of commission (%)		Kappa	
		Built-up	Non-built-up	Built-up	Non-built-up	Built-up	Non-built-up
São Miguel	95.5	25	2.72	29.41	2.19	0.75	0.97
Madeira	92.5	43.7	4.35	47.06	3.83	0.56	0.96
Gran Canaria	95.5	38.46	2.14	33.33	2.66	0.62	0.98
Tenerife	94	43.75	2.72	35.71	3.76	0.56	0.97

4.1.4. Settlement typology

Quantitative results from the proposed settlement typology are presented in table 3. These were calculated for each settlement type as percentage of settled area (%settled area) and percentage of island area (%island).

Table 3. Islands' settlement typology

	Main settlement		Consolidated settlement		Fragmented settlement		Dispersed settlement	
	%settled area	%island	%settled area	%island	%settled area	%island	%settled area	%island
São Miguel	26.15	2.16	51.51	4.25	20.41	1.68	1.95	0.16
Madeira	23.5	1.96	38.71	3.22	33.48	2.79	4.36	0.36
Gran Canaria	11.53	0.74	54.69	3.50	28.41	1.82	5.36	0.34
Tenerife	20.58	1.23	47.63	2.85	28.27	1.69	3.53	0.21

4.2. Multinomial logit model

A multinomial logistic regression model for the probability that a pixel (case) belongs to one of the four aforementioned settlement classes was estimated. The presence of a relationship between the dependent and combination of independent variables is based on the statistical significance of the final model chi-square in table 4. The chi-square based maximum likelihood ratio test was used to evaluate the overall model fit and to estimate the significance of each terrain attribute in influencing the spatial distribution of settlements.

In all the islands, the overall multinomial logistic model was found to be significantly fit ($p<0.01$). By including the predictor variables and maximizing the log likelihood of the outcomes seen in the data, the "Final" model improves upon the "Intercept" model in every island (table 4). This can be seen in the differences in the -2 (Log Likelihood) values associated with the models. The null hypothesis that there was no difference between the model without independent variables and the model with independent variables was rejected. Thus, the existence of a relationship

Rodrigues, M. (2015): "A spatial typology for settlement pattern analysis in small islands", GeoFocus, nº15, p. 3-26. ISSN: 1578-5157

between the independent variables (terrain attributes) and the dependent variable (settlement typology) was supported.

Table 4. Fitting information

			São Miguel	Madeira	Gran Canaria	Tenerife
Model fitting criteria	-2 log likelihood	Intercept	148915.006	163360.654	237956.290	311797.574
		Final	116689.939	152179.702	203218.042	299359.687
Likelihood ratio tests	Chi-square		32225.067	11180.952	34738.248	12437.887
	df		12	12	12	12
	Sig.		0.000	0.000	0.000	0.000

Table 5 shows which of the independent variables (terrain attributes) as a whole are significantly related to the dependent variable (settlement types). It also shows that all predictor variables used in the multinomial logistic models, for each island, were found to be statistically significant ($p < 0.01$).

Table 5. Likelihood ratio tests

	Chi-square			
	São Miguel	Madeira	Gran Canaria	Tenerife
Intercept	16866.707	3602.355	16608.103	7479.827
Aspect	816.859	1117.197	299.511	2539.771
Altitude	22176.681	8227.656	624.489	2265.922
Dist. to coast	3751.794	2418.485	5506.051	5099.084
Slope	453.867	1218.69	1017.299	2006.012
For all the models: df.= 3; Sig. = 0.000				

A useful measure to assess a multinomial logistic regression model is classification accuracy, which compares predicted group membership, based on the logistic model to the actual, known group membership, which is the value for the dependent variable. Table 6 shows how well the model correctly classified islands' cases (cells).

Table 6. Model classification accuracy

	Percent correct			
	São Miguel	Madeira	Gran Canaria	Tenerife
Main settlement	63.9	28.2	2.3	19.4
Consolidated settlement	75	47.6	90.7	90.4
Fragmented settlement	23.4	46.1	36.5	7.7
Dispersed settlement	7	0	0	0
Overall percentage	60.2	40.5	60.6	49.3

Rodrigues, M. (2015): "A spatial typology for settlement pattern analysis in small islands", GeoFocus, nº15, p. 3-26. ISSN: 1578-5157

The overall predictive accuracy of a model is based on the percent of correct predictions, comparatively to the rate of accuracy achievable by chance alone (table 1). A 25% improvement over the "accuracy achievable by chance alone", allows to characterize the multinomial regression as useful (Costea & Eklund, 2003), as such, São Miguel (1.25*0.3768= **47.1%**); Madeira (1.25*0.3186= **39.83%**); Gran Canaria (1.25*0.3993= **49.91%**); Tenerife (1.25*0.3507= **43.84%**). Thus, for every model the classification accuracy rate showed a value greater than a 25% improvement over the rate of accuracy achievable by chance alone (table 1), suggesting that the models were useful.

6. Discussion

Finding appropriate data representative of settled area is always a time and effort consuming process. In this study, morphological settlement areas (MSAs) were defined at a large scale, producing areas with no administrative meaning. The proposed MSAs are aggregated continuous surfaces of built-up tissue void of road-network; the absence of road network prevents having individual MSAs merged together. Like any cartographic representation, MSAs represent a model of the islands' reality and as such have errors, including errors consciously introduced in the road network removal and in the process of 30 meters built-up aggregation. This process was responsible for the higher values obtained for the omission and commission errors (table 2), since the applied method erased built-up areas from road network (increasing the omission error). Moreover, the dilation and erosion operators do not preserve the initial shape of the built-up areas (increasing the commission errors). This implied that several portions of non-built-up areas would end in the MSAs datasets as built-up due to patch aggregation (figure 3).

The analysis of the MSAs' typological classification allows to gain an insight into the islands' settlement pattern. "Main settlement" shows the weight of the main city in the islands' settled area. Table 3 shows that the island of São Miguel stands out, with the city of Ponta Delgada holding 26.15% of the settled area. This value drops to 23.5% for the city of Funchal in Madeira, 20.58% for Santa Cruz de Tenerife in Tenerife and 11.53% for the largest city of Gran Canaria, Las Palmas. Results from the proposed settlement typology reveal that the island of São Miguel has the most concentrated settlement pattern among the analysed islands, since only 1.95% of its settled area consists of "dispersed settlements" and it also has the lowest value of "fragmented settlements" among its MSAs (20.41%). Adding the "dispersed" and "fragmented" settlements values, the typology indicates that among the analysed islands, Madeira has the most scattered settlement, with 37.84% of its MSAs being fragmented or dispersed. One of the method's drawbacks is that, since the proposed settlement typology is exclusively morphological, it is not possible to incorporate functional variables to identify complex spatial dynamics, such as polycentrism. Nonetheless, this typology may be tailored to incorporate its morphological dimension into broader multidimensional approaches. Ultimately, the study's settlement typology is not an end in itself, but a tool to develop further studies.

Showcasing the application of the proposed settlement typology in a systematic and representative analysis, the multinomial logistic regression came up with a number of useful results:

Rodrigues, M. (2015): "A spatial typology for settlement pattern analysis in small islands", GeoFocus, nº15, p. 3-26. ISSN: 1578-5157

Firstly, findings revealed the existence of a relationship between the independent variables and the dependent variable (table 4), since the probability of the models chi-square was less than the level of significance, suggesting that there was a statistically significant relationship between the independent physical variables and the dependent variable (settlement typology). Secondly, for the selected terrain attributes, modelling showed which ones are more influential in the islands' spatial distribution of settlements. Table 5 shows that the most significant terrain attribute was found to be "altitude" in São Miguel and Madeira and "distance to coastline" in Gran Canaria and Tenerife. Empirical knowledge of the islands' landscape suggest that in Gran Canaria and Tenerife there is a higher pressure for settlements to be closer to the shoreline due to tourist activities, on the other hand, São Miguel and Madeira do not have sandy beaches. For every model, the overall classification accuracy rate showed a value higher than a 25% improvement over the rate of accuracy achievable by chance alone (table 1 & 6), suggesting that the models were useful. Nonetheless, we can observe that the overall predictive accuracy is not fundamentally higher than the minimum threshold, in Madeira it is only 0.67% higher: São Miguel (60.2% - 47.1% = 13.1%); Madeira (40.5% - 39.83% = 0.67%); Gran Canaria (60.6% - 49.91% = 10.69); Tenerife (49.3% - 43.84% = 5.46%). This confirms that the settlements' spatial variation is explained by a set of interconnected driving forces not present in the applied model.

The applied model indicates that the selected physical variables are not relevant to the location of some types of settlement. In fact, the selected physical variables play a small role in the location of "fragmented settlement", where the classification accuracy ranges between 7.7% (Tenerife) to 46.1% (Madeira). Moreover, it cannot explain the "dispersed settlement", since the classification accuracy varies between 0% (Madeira, Gran Canaria and Tenerife) to 7% (São Miguel). Nonetheless, the study's settlement typology, coupled with the MNL model, might be a major asset in studying the spatial determinants of land change in these territories. Analysing the role of the terrain in this small volcanic islands, might help to identify the influences and interactions involving socio-economic and physical driving forces into the islands' land change. Assuming that physical conditions remain unchanged over the time-span of a land change analysis, a researcher might be able to distinguish between land change driving forces, knowing beforehand the measure to which terrain attributes influence settlements. In fact, this is just an example of the possibilities of the proposed settlement typology.

7. Conclusion

The study's research problem addressed the islands' lack of large scale spatial data, while providing a methodological basis for mapping and typological classification of settlements. Showcasing the application of the proposed settlement typology to a systematic and representative analysis, the MNL model measured the impact that the terrain has in the location of settlements types across these islands. Research has shown that the islands' settlement pattern is not uniform, and that there are strong asymmetries within the islands, which, as expected, are not explainable by resorting only to the physical variables used in the model. The study's major contribution relies in the mapping and typological classification of the islands' settlements. The applied method is straightforward to implement, allowing the creation of high-resolution datasets and opening

Rodrigues, M. (2015): "A spatial typology for settlement pattern analysis in small islands", GeoFocus, nº15, p. 3-26. ISSN: 1578-5157

possibilities for subsequent studies, namely spatio-temporal analysis. MSAs clearly show the islands' settlements, with the method being particularly useful for regions where there are no available data. The large scale for which mapping was conducted, shows in detail where settlements take place, with the advantage that it allows the acquisition of city boundaries, since the MSAs define the outer perimeter of settlements. It was not in the immediate purpose of this study to develop the ultimate settlement typology. This study acknowledges the complex nature of human settlements and realises the difficulties in defining specific categories. The purpose of the settlement typology applied here, is therefore, to provide a tool for the systematic and representative analysis of settlements, based solely on a morphological dimension. The proposed typological classification criterion was spatially restricted, not considering any socio-economic thresholds; nonetheless it allowed to differentiate settlement patterns among islands. Avoiding the use of socio-economic variables allows the classification of multiple landscapes while maintaining the same classification thresholds, a significant feature that allows this proposed settlement typology to be applied to other regions and/or data sources. In conclusion, the applied method of settlement mapping and typological classification, contributes to a better understanding of settlements patterns, and may be seamlessly applied to other small islands elsewhere, overcoming traditional data constraints and being an asset in the decision-making framework for planning in general.

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V. Conclusions

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5.1. Conclusions with regard to the research aim

The aim of this research was to propose novel methods for quantifying and visualizing geographical information that aids the spatial planning decision-making process when addressing LULC patterns. The approach involved using spatial modeling approaches and novel geographic representations that stress the importance of the role geographic visualization has for spatial planning. Therefore, this research is an example of the application of geographic visualization for knowledge-building purposes. The proposed methods allowed exploring and analyzing multivariate geospatial data to answer complex geographical research questions, and facilitate the analysis of LULC patterns across the Macaronesian islands of Portugal and Spain. Overall, the LULC assessments with the proposed methods produced accurate information about the islands' landscape and their anthropogenic patterns of land change. The research contributed to the scientific research of territories that have been overlooked in comparative LULC research by trying to promote the sustainable development debate with respect to anthropogenic land change. Consequently, it is important to note that in addition to pure scientific research, this thesis also sought to raise the awareness about the sustainable development of these archipelagos.

Graphical representations of LULC provide valuable information for planners and land resource managers. Furthermore, the ability to integrate multivariate data in a single graphical presentation within a spatially explicit context provides a valuable tool. This research proposed three novel 2D static graph-based methods for representing geospatial data (Rodrigues 2016; 2016c; 2016d). The first objective of this research proposed a novel method for representing and analyzing LULC patterns and trends (Rodrigues 2016c). The proposed method can be a valuable asset for analyzing and presenting a snapshot of broad LULC patterns and trends on not merely islands, but elsewhere.

The second objective of this research proposed a novel method for representing and analyzing coastal patterns (Rodrigues 2016). This research proposed the coastal zonation chart (CZC) as a novel method for studying geospatial data across the islands' coastal areas. The proposed method is a 2D static graph-based method of summarizing coastal patterns of geospatial data into arc/sectors of a graph by setting up spatial units of analysis based on compass directions suitable to organize, analyze, and depict geospatial data. The CZC method can be used to: (1) easily draw visual impressions of coastal data, (2) facilitate comparisons among study areas, and (3) uncover underlying trends of coastal change. The CZC is a subjective representation of an island coast. It is a flexible, spatially explicit, and meaningful graphical method, capable of representing coastal LULC data of islands and is suitable for broader applications. The method allows an easy detection of patterns and visualization of similarities and differences between two or more sets of coastal geospatial data. As demonstrated, the method is suitable for effective evaluations of coastal LULC gains and losses.

The third objective of this research proposed a novel method for representing and analyzing altitudinal patterns (Rodrigues 2016d). Once again, the method relies on a GIS-based spatial analysis and displays a graphical representation of the information in a custom-made chart call an Altitudinal Zonation Radial Chart (AZRC). This research proposed the AZRC as a novel method for studying geospatial data across altitudinal gradients. The AZRC can be used to: (1) improve the presentation of geospatial data for an efficient understanding of altitudinal zonation, (2) facilitate visual comparisons among study areas and/or time-series, and (3) convey and enhance the understanding of geospatial data in a spatially explicit and meaningful manner to uncover underlying altitudinal spatial trends. The method is flexible, spatially explicit and meaningful, and suitable for application in other regions. The results highlight that this novel 2D static graph-based method summarizes vast amounts of information and facilitates the identification of spatial patterns and trends by determining altitudinal patterns.

In the proposed three methods of geographic visualization, geospatial data is replaced by an indirect, graphical representation of this data that summarizes the information. This approach allows a simultaneous representation of multivariate data in a single graphical presentation or data view. Because the proposed methods may be easily customized, they can further incorporate their graphical dimension into broader multidimensional approaches to landscape analysis. Therefore, the methods herein presented make drawing visual impressions of geospatial data while summarizing vast amounts of information easy through facilitating the identification of spatial patterns and trends in a straightforward, spatially explicit, and meaningful manner. Thus, the first three research objectives were devised to provide novel methods for visualizing geographical information.

The fourth and fifth research objectives were dedicated to GIS-based modeling approaches (Rodrigues 2015; 2016b) to provide novel methods for quantifying geographical information. The fourth objective of this research proposed a novel method for deducing and representing land development pressure (Rodrigues 2016b*).* This research assumes that, due to LULC driving forces, land development pressure is the magnitude of a landscape's artificial land change, and that this magnitude can be represented with a gradient surface. The same modeling method can be applied to any other region in order to deduce the anthropogenic spatial impact from land development pressure. The fourth objective led to a novel spatial modeling approach allowing the quantification and representation of land development pressure, a crucial anthropogenic spatial process affecting environmental sustainability. The method allows a spatially explicit representation of land development pressure and should be a valuable tool as these results can be used as inputs for other on LULC driving forces.

To conclude the research the fifth objective proposed a novel morphological typology for settlement patterns (Rodrigues 2015). The results made it possible to accept the hypothesis that the importance of topographic variables is statistically significant in the location of settlements on these islands. The applied method contributes to a better understanding of settlement patterns and may be seamlessly applied elsewhere. It also overcomes traditional data constraints, and is therefore an asset in the decision-making framework for spatial planning.

This thesis proposes novel geographic representations and spatial modeling approaches designed to fulfill the demands of LULC analysis; however, it is important to note that the potential application(s) of such techniques is not constrained only to LULC spatial decision-support systems. In fact, the representation of the landscape through these novel methods, depicting and quantifying space in a multiplicity of ways, opens several research prospects. Therefore, the proposed modeling and geovisualization techniques presented throughout this research allow not only answer locational-level questions, but also provide answers to other higher-order decision-making and content-knowledge-building questions. Ultimately, this is the reason why the thesis title is about new methods for quantifying and visualizing information from “spatial patterns,” rather than “LULC patterns”.

5.2. Conclusions with regard to the research questions

Due to the journal's requirements, the presentation of the findings could not been addressed in the first three articles, which focus solely on the methodological approaches of novel geographic visualizations. As a result, the findings concerning the first three articles had to be presented elsewhere. Therefore, a choice was made to present the key findings of the first three research questions in this last chapter. The conclusions of the fourth and fifth research questions are shorter in order to avoid the redundancy of transcribing the findings presented in the fourth and fifth article.

5.2.1. First research question

What are the contemporary land use patterns and trends on the Macaronesian islands of Portugal and Spain?

The published map (Rodrigues 2016c) describes the land area totals by land use category for two years: 1990, and 2006. The map also reveals the land use midpoint percent change from 1990 to 2006. The midpoint method is a technique for calculating the percent change in a variable compared with the average (midpoint) of the starting and final values. Midpoint percent change was computed as:

$$\%\Delta[Midpoint] = \frac{V_1 - V_0}{\left(\frac{V_1 + V_0}{2}\right)} \times 100$$

Where 'V_0' represents the initial value and 'V_1' is the later value.

The published map provides an overall understanding of the land use patterns and recent trends on the Macaronesian islands of Portugal and Spain. The results demonstrate that, between 1990 and 2006, artificial surfaces increased on every island, essentially expanding at the cost of the agricultural areas because the majority of the remaining natural areas are protected. Due to a high percentage of agricultural land use, the Azores archipelago has few forests/semi-natural areas when compared with Madeira and the Canary Islands. The results demonstrate that in the Azores, the islands with the largest patches of forests/semi-natural territory are Pico (Figure A5), Flores (Figure A2), and Corvo (Figure A1), which, as of 2006, were the only Azorean islands with more than 50 percent of the land use being forests/semi-natural.

Because this analysis uses the CORINE land cover level 1, data is considerably aggregated at this level. Thus, differentiating between forests and semi-natural areas is not possible. Consequently, it is important to note that, despite having large semi-natural areas, some of the islands are practically deforested (e.g. Corvo) or too arid to have significant forested areas (e.g. Porto Santo, Fuerteventura and Lanzarote).

In the last decades the tertiary sector surpassed the primary sector and agricultural activities lost economic importance on the islands. Nonetheless, the results demonstrate that, as of 2006, agricultural land use still dominated the Azores landscape. One should note that the agricultural production in the Azores differs substantially from the small cultivation fields in the Canaries and Madeira. In the Azores, livestock and dairy production are the main agricultural activities. Consequently, the Azores' agricultural areas are dominated by vast grasslands with semi-natural pastures and meadows, rather than by small cultivation fields as in the other two archipelagos.

The results also demonstrate that, within the archipelagos, there are significant differences among the islands. Although the Azorean islands of Corvo and Flores are the most sparsely populated islands among the three archipelagos (< 30 inhab./km^2), the islands of Pico (Figure A5) and São Jorge (Figure A6) have a relative lower amount of artificial surfaces. In this respect one interesting finding was, as of 2006 Tenerife (Figure A13) with 419 inhab./km^2 and Gran Canaria (Figure A14) with 547 inhab./km^2 had artificial territories of 8.16 and 7.72 percent of their landscapes, respectively. Surprisingly, Lanzarote (Figure A16) with 151 inhab./km^2 in 2006, had a higher proportion of artificial surfaces at 9.76 percent, the highest in the Canaries. The island of Lanzarote is a good example of the disparity in the settlement morphology among the islands. Lanzarote has a low population density compared to the amount of artificial territory because the island does not present the common high-rise buildings of Tenerife and Gran Canaria and favors a very low urban form density.

As of 2006 in the Madeira and Canary islands, forests/semi-natural areas remained the predominant land use type with several islands having more than 70 percent of the surface covered by forests/semi-natural areas: Porto Santo (Figure A18), La Palma (Figure A11), La Gomera (Figure A10), and Fuerteventura (Figure A15). However, despite having large natural areas, the Madeira and Canary Islands diverge on the relative amount of artificial land use. As of 2006 the Madeira archipelago had by far the highest proportion of landscape covered with artificial surfaces. In contrast, the Azores had a much lower relative proportion of landscape covered with artificial surfaces.

The results of land use trends reveal that, at the turn of the millennium, the expansion of artificial surfaces was the most significant LULC trend affecting these islands. The last decades of the twentieth century were marked by a significant shift in LULC dynamics. Agricultural activities ceased to be the main driving force behind land change and were replaced by a rampant increase of artificial surfaces. Between 1990 and 2006 the artificial surfaces have increased on every island, with the exception of São Jorge (Figure A6). Midpoint percentages of artificial surfaces range from 7.11 percent (Pico, Figure A5) up to a staggering 86.72 percent (Fuerteventura, Figure A15). Overall, across the three archipelagos, the major land use changes occurred through the conversion of agricultural areas into artificial surfaces. Nonetheless, on some islands such as Madeira (Figure A17), Gran Canaria (Figure A14), and Fuerteventura (Figure A15), land change had also consumed significant forest/semi-natural areas. Additionally, considerable variability exists regarding the amount of land use areas that changed over the 16-year study period. The island with the most change in terms of overall land use (as percent of total surface area) was the island of Graciosa (16.61 percent) followed by Gran Canaria (14.5 percent). The island with the least was the Azorean island of Flores, where only 0.68 percent of the island's land use changed over the 16-year study period.

When focusing on individual islands, the published map (Rodrigues 2016c) reveals that in percentage terms, during the 16-year period the largest increase in artificial surfaces occurred in Fuerteventura (86.72 percent), followed by La Palma (78.06 percent), La Gomera (58.56 percent), and Madeira (43.01 percent). The lowest artificial surface increase occurred in the Azorean islands of Pico (7.11 percent), Terceira (13.43 percent) and Santa Maria (14.67 percent), while another Azorean island, São Jorge (Figure A6), maintained the same relative amount of artificial surface over the 16-year period. Overall, this artificial expansion was responsible for major reductions of agricultural areas. In the mid-twentieth century, owing to profound social and economic changes, the tertiary sector started its rise to become the main economic sector. Because the secondary sector in this region has always been minor, this substantial shift to the tertiary sector dictated a progressive abandonment of the primary sector. Hence, agricultural areas started to recede. In fact, a key factor from the 16-year period between 1990 and 2006 revealed that agricultural areas have decreased on every island, with the exception of the Canary Islands of La Gomera (Figure A10) and Fuerteventura (Figure A15), which registered an increase of their agricultural areas by 3.43 percent and 17.73 percent, respectively. The agricultural land use decrease was most significant in the Madeira archipelago, where it ranged from a decrease of 23.51 percent in Porto Santo (Figure A18) to 23.05 percent in Madeira (Figure A17).

Across the archipelagos the forests/semi-natural land use was the most stable category, mostly due to the strict protection of these areas. Thus the bulk of LULC change is confined to the artificial and agricultural areas. Even so, all the Canaries and Madeira Islands decreased their forests/semi-natural areas. However, because the majority of the forests are protected areas, the majority of the change has occurred in the semi-natural areas. Across the forests/semi-natural areas significant losses occurred in Fuerteventura (4.74 percent), Terceira (2.85 percent) and Madeira (2.08 percent). Increases were observed in Graciosa (25.23 percent) and São Jorge (2.22 percent). It is important to note that, in this region the majority of the natural areas are strictly protected because of their recognized ecological values. For instance, this recognized ecological value has allowed the laurel forest in the Madeira Natural Park to become a UNESCO World Heritage Site[20].

Regarding the main islands, five centuries of anthropogenic impacts were responsible for the deforestation of São Miguel, whereas Madeira, Gran Canaria, and Tenerife were able to maintain large patches of forests because of their rugged terrain. In São Miguel (Figure A8), the most striking feature is the extensive agricultural areas across the island. Figure A8 reveals that, as of 2006 the majority of São Miguel's landscape consisted of agricultural areas, followed by forests/semi-natural areas inland, while the artificial surfaces occupied only small areas on the coast. Among the Macaronesian islands of Portugal and Spain, São Miguel is one of the islands that suffered the most significant anthropogenic land change, which changed more than two-thirds of its landscape to human land use. São Miguel has lost nearly all of its dense laurel forests that once blanketed the island. What remains today is primarily in protected areas. As of 2006 only about 27 percent of the landscape remained with forests/semi-natural uses (Figure A8). It is important to note that São Miguel's lower altitude and gentler slopes, when compared with the other main islands, facilitated agricultural exploration. This intensive agricultural exploration dramatically changed the island's landscape. Nonetheless, one should note that, in the last decades, São Miguel's agricultural activities focused on the establishment of livestock production systems. Consequently, the agricultural landscape is dominated by grasslands, which somewhat moderates the visual impact across the landscape. Fortunately, artificial surfaces consume a very low amount of the landscape. As of 2006 the artificial areas occupied only about 4.73 percent of the landscape (Figure A8), by far the lowest proportion among the main islands. In terms of trends, São Miguel's land use was relatively stable between 1990 and 2006. Figure A8 reveals that as of 1990, 69.48 percent of the landscape was occupied by agricultural areas, 26.7 percent by forests/semi-natural areas, while artificial areas occupied 3.82 percent. Sixteen years later, a slight decrease had occurred in agricultural areas, which lost surface area primarily to the expansion of artificial surfaces. Overall, Figure A8 reveals that over the 1990-2006 period, 4.03 percent of São Miguel's landscape changed, with the majority of the land change occurring due to land change transitions into artificial surfaces and a very small increase in forests/semi-natural areas.

Figure A17 describes Madeira's land use in 1990 and 2006. The predominant category was forests/semi-natural land use, which was located all across the island. Figure A17 further

[20] A place that is listed by the United Nations Educational Scientific and Cultural Organization (UNESCO) as being of special cultural or physical significance.

reveals that artificial and agricultural land use is concentrated in the southern coastal areas. Because of the island's steep slopes and high cliffs, Madeira was the one with the highest proportion of forests/semi-natural land use compared with the other main islands. More than two-thirds of Madeira's landscape is forests and semi-natural areas. Nonetheless, one should note, "land-use change is likely to cause land-cover change, but land-cover may change even if the land-use remains unaltered" (Turner and Meyer 1994: 5). Therefore, albeit having a natural use, these areas were directly or indirectly affected by anthropogenic impact over the years. Therefore, notwithstanding the natural land use, the land cover in these areas has been greatly altered since colonization in the fifteenth century. Even so, Figure A17 reveals that as of 1990, 70.05 percent of Madeira's landscape was occupied by forests/semi-natural areas, 19.84 percent by agricultural areas, and only 10.11 percent by artificial surfaces. In 16 years, the most significant trend was the sharp increase that has occurred in artificial surfaces, which expanded their surface mainly at the cost of agricultural areas receding to 15.74 percent of the landscape. Nonetheless, the forests/semi-natural areas also receded to a landscape proportion of 68.61 percent. Overall, Figure A17 reveals that over the 1990-2006 period, 7.73 percent of Madeira's landscape changed and the bulk of the change was due to converting agricultural areas into artificial surfaces.

Figure A14 describes Gran Canaria's land use between 1990 and 2006. Forests/semi-natural areas are the predominant category, whereas agricultural and artificial areas are mainly located on the island's northeastern areas. Although maintaining more than two-thirds of the landscape with a forests/semi-natural land use, Gran Canaria has suffered a more intensive anthropogenic impact compared to Madeira. As a result, nowadays the island has only 1 percent of its former laurel forest compared with Madeira's 25 percent (Fernández-Palacios et al. 2011: 240). Regarding LULC trends, Figure A14 reveals that, as of 1990, 67.58 percent of Gran Canaria's landscape was forests/semi-natural areas, 27.15 percent was agricultural areas, and 5.27 percent was artificial surfaces. In 16 years the greatest change has occurred with artificial surfaces, which gained surface area mostly at the cost of agricultural areas, since the decrease in forests/semi-natural areas was lower. Overall, Figure A14 reveals that over the 1990-2006 period, 14.5 percent of Gran Canaria's landscape changed, with the majority of the land change due to agricultural areas being transformed into artificial surfaces.

Similarly to Gran Canaria, Tenerife's predominant category in 2006 was forests/semi-natural, whereas agricultural and artificial land uses were mainly located in the northeast. Nonetheless, owing to the high cliffs and ravines, Tenerife natural areas suffered less anthropogenic impact when compared with Gran Canaria and maintains 15 percent of its laurel forest (Fernández-Palacios et al. 2011: 240). Figure A13 reveals that as of 1990, 67.11 percent of Tenerife's landscape was occupied by forests/semi-natural areas, 27.59 percent by agricultural areas, 5.3 percent occupied by artificial surfaces. In 16 years the increase in artificial surfaces occurred predominately at the expense of agricultural areas and a very slight decrease in forests/semi-natural areas. Overall, Figure A13 reveals that over the 1990-2006 interval, 9.81 percent of Tenerife's landscape changed. The majority of Tenerife's landscape change was due to converting agricultural areas into artificial surfaces.

The results have revealed that, in the last decades, the islands of Terceira (Figure A9), La Gomera (Figure A10), Fuerteventura (Figure A15), and Lanzarote (Figure A16), have suffered some of the most damaging ecological LULC changes by transforming several forests/semi-natural areas into artificial surfaces. Unlike to land change into agricultural areas, changes into artificial surfaces are irreversible. Once natural areas are lost to artificial surfaces, they are lost forever. The results reveal that in a time-span of only 16 years (1990-2006), land change made a noticeable impact on the islands' landscapes, giving them new areas for the spread of artificial surfaces and the recession of agricultural areas. The analysis of the published map reveals a number of changes and enables the quantification of the major trends that have occurred across the islands. These findings were achieved resorting to a novel graphical method of representing LULC patterns and trends. Understanding LULC patterns requires an array of methods that highlight hidden landscape dynamics. The published map (Rodrigues 2016c) is an example of how geographic visualization methods can help policy-makers and researchers uncover useful information from GIS-based analysis by turning numbers from tables into a comprehensive figure about patterns and rates of LULC change.

5.2.2. Second research question

What is the contemporary pattern of coastal land use on the main islands?

The last decades of the twentieth century were marked by a significant shift in LULC dynamics across this region. As mentioned earlier, agricultural activities ceased to be the main driving force behind land change and were replaced by a rampant increase of artificial surfaces, mainly on the drier leeward southern coastal areas where tourism- and real estate-related pressures cause a major impact on the landscape. A direct consequence of this pressure was the drastic transformation across the islands' coastal landscapes. When devising a coastal land use analysis to address the second research question, this research employed a GIS-based spatial analysis. The results are visualized in a custom-made chart called a CZC (Coastal Zonation Chart), a novel geographic visualization method (Rodrigues 2016). When applying the proposed method, the four main Macaronesian islands of Portugal and Spain displayed asymmetric coastal land use patterns, with coastal areas experienced the greatest land use change (Figures A19-

A22). A major difference among the four islands is that São Miguel and Madeira's coastal artificial expansion took place in areas with major cities because of urban dynamics. Gran Canaria's and Tenerife's coastal artificial expansion did not take place in the areas of the capital cities (i.e. the northeast), but rather in the more sparsely populated southern coastal areas. This occurrence is the cause of tourism development.

In São Miguel a visual comparison between years reveals few changes over the 16-year period. Using the CZC method (Rodrigues 2016), Figure A19 reveals the lower relative proportion of artificial and forests/semi-natural areas along a 5 km coastal strip. On the contrary, the agricultural areas had in some coastal zones, a relative occupation of almost 100 percent (e.g. the 0-1 km coastal zone in the North-Northeast [NNE] sector). In addition, Figure A19 reveals that, although occupying a relatively limited area in total, the artificial coastal surfaces were predominately located in São Miguel's North-Northwest (NNW) and West-Southwest (WSW) sectors, in other words the Ponta Delgada and Ribeira Grande areas. The East-Northeast (ENE) and (ESE) sectors were void of artificial surfaces along the 5 km coastal strip. Overall, the 0-1 km coastal zone had the majority of the artificial surfaces. Nonetheless, its relative proportion never reached more than 50 percent in any of the coastal sectors. Another key finding is that, between 1990 and 2006 the only noticeable spatial trend was that coastal land development had slightly spread the artificial surfaces in the NNW and South-Southeast (SSE) sectors (the Ponta Delgada and Vila Franca do Campo areas, respectively). In these sectors the artificial expansion was made at the expense of a reduction in agricultural areas because figure A19 reveals that in the NNW sector, the forests/semi-natural areas were nonexistent, and albeit low in 2006, they had remained identical in the SSE sector.

Figure A20 reveals the spatial distribution of land use along Madeira's 5 km coastal strip. The immediate observation is that the artificial surfaces are concentrated along the southern sectors and in the CZC's outer rings (i.e. closest to the coastline). In 1990 the artificial coastal surfaces were mainly concentrated in the WSW, South-Southwest (SSW), and SSE sectors. Agricultural areas are located predominantly in the WSW, SSW, and East-Northeast (ENE) sectors, and forests/semi-natural areas in the NNW, NNE, and East-Southeast (ESE) sectors. In 1990 the 0-1 km coastal zone was principally occupied by artificial surfaces, with the occupation decreasing further inland. The SSE and WSW sectors had more than 50 percent of their area occupied with artificial surfaces in this 0-1 km coastal zone. Compared with São Miguel, Madeira has a coastal land use pattern more greatly dominated by artificial surfaces. Contrary to São Miguel, Madeira does not maintain its overall pattern of land use along the 5 km coastal strip. In other words, Madeira's inland is dominated by forests/semi-natural areas (Figure A17). However, the reality across the coast is very different. In fact, Figure A20 reveals that only in the northern coastal sectors did Madeira maintain a majority of forests/semi-natural areas. A visual comparison between years reveals a striking change in the southern coastal areas over the 16-year period. The most obvious change is the great increase in artificial surfaces. Between 1990 and 2006, Madeira's artificial surfaces clearly expanded on the southern and southeastern areas, (the Câmara de Lobos and Funchal areas and the Caniço area, respectively). This spatial trend reflects the location of Madeira's main cities, which are concentrated along the southern coastal areas. Additionally, between 1990 and 2006, the WSW, SSW, and SSE sectors had the highest increase of artificial surfaces. Furthermore, as of 2006, the SSE sector had occupations of artificial surfaces higher than 50 percent in all coastal zones, with occupations even exceeding 70 percent in the zones up to 4 km from the coastline.

Focusing now on Gran Canaria, the CZC method (Rodrigues 2016) in Figure A21 reveals the spatial distribution of land use along Gran Canaria's 5 km coastal strip. Figure A21 reveals that, as of 1990 the western coastal areas of Gran Canaria were almost free of artificial surfaces, with the exception of the SSW sector where tourism-related infrastructure is concentrated on the Maspalomas area. This spatial pattern somewhat prevailed in 2006. One should note that the eastern coast of the island has gentler slopes, whereas the western coast is rockier and mountainous. Between 1990 and 2006 there was a marked increase in the artificial surfaces of the SSW zones up to 4 km from the coastline. This is the cause of tourist resort development concentrated in the south, which favored coastline proximity. In 1990 the 0-1 km coastal zone had the highest relative occupation of artificial surfaces, with the value decreasing further inland. The ENE and ESE sectors had the highest occupation of artificial surfaces. However, the occupation of artificial surfaces did not exceed 50 percent in any coastal zone from these sectors. In 2006 the 0-1 km coastal zone remained the zone with the highest artificial surface occupation. Moreover, the SSW sector experienced the greatest increase in artificial surfaces, although the highest percentages remained in the ENE and ESE sectors. With Figure A21 it is possible to observe that most of the island’s artificial surface increase was located up to 2 km from the coastline. Taking into account all the coastal zones along the 5 km coastal strip depicted in Figure A21, Gran Canaria’s ENE sector, which includes the Las Palmas area, experienced the greatest increase in artificial surfaces. This is most visible in the 0-1, 1-2, and 2-3 km coastal zones. Nonetheless, across the island the highest increase in the 0-1 km coastal strip occurred in the SSW sector, which is the Maspalomas area. Figure A21 reveals that this increase was made predominately at the expense of forests/semi-natural areas. Through the figure one also observes that in the ENE sector the artificial surface increase occurred at the expense of agricultural areas, while in the NNE sector the artificial surface increase consumed forests/semi-natural areas. In fact, along the island’s coast the forests/semi-natural areas remained identical between 1990 and 2006. The exceptions were the NNE and SSW sectors, where the artificial surface increase was made at the expense of reducing forests/semi-natural areas.

Again by using the CZC method (Rodrigues 2016) Figure A22 reveals the spatial distribution of land use along Tenerife's 5 km coastal strip. After São Miguel, Tenerife had the second lowest relative occupation of artificial surfaces along the 5 km coastal strip. As of 1990 artificial surfaces were concentrated on the northeastern and southwestern sectors of the island. Between 1990 and 2006, Tenerife's expansion of artificial surfaces took place in the NNE, SSW, and SSE sectors. The artificial surface expansion was very noticeable along the 5 km coastal strip of the SSW sector across the Costa del Silencio area. In similarity with Gran Canaria, expansion occurred because of tourist resort development on the island's leeward south. Nonetheless, none of Tenerife's coastal zones up to 5 km from the coastline had a sector occupied by more than 40 percent artificial surfaces. It is important to note that, in these islands tourism is more prevalent in the southern (i.e. leeward) coastal areas, which are hotter and drier.

Overall, on all of the four main islands, one can verify that along the coast the majority of the artificial surface expansion was made at the expense of agricultural areas. Encouragingly, the coastal forests/semi-natural areas did not experience significant changes between 1990 and 2006. However, there are two exceptions: (1) agricultural areas replaced forest/semi-natural areas in Gran Canaria's NNE sector, and (2) artificial surfaces consumed forest/semi-natural areas in Gran Canaria's SSW sector. Overall as shown, the alternative visualization of the islands' coastal land use permits a novel insight into the overall LULC patterns and trends across these territories.

5.2.3. Third research question

What is the contemporary altitudinal pattern of land cover on the main islands?

After answering the second research question, coastal land use patterns are clearer for the main islands. Nonetheless, distance to the coastline is not the only impeding physical factor acting as a LULC driving force. The vertical organization of the landscape is an important factor to account for in spatial planning, especially in rugged and mountainous landscapes. Altitude alone is an important factor in determining land cover patterns. In these rugged volcanic islands, altitude and slope also constrain much of the LULC dynamics. A key finding from the second question research is a coastal land use dichotomy between the northern and southern ends of the islands. The Azores high-pressure system is responsible for the northerly and northeasterly trade winds prevalent in the archipelagos and largely determines the climate on these islands. This phenomenon creates dissimilar climatic characteristics between the windward and leeward slopes of the mountainous islands. Orographically induced adiabatic cooling leads to the development of a cloud belt responsible for orographic precipitation on the windward side. Because of these conditions, there exists a visible north/south landscape dichotomy, which is also present in land cover patterns. Much of the rainfall received is on these areas because the windward northwestern slopes temperature is cooler and the relative humidity of the air is higher. In contrast, the leeward southern slopes are warmer, sunnier, and dryer. On the one hand, the precipitation generated by the forced condensation of air encountering elevated terrain determines much of the islands' natural land cover distribution. On the other hand, the anthropogenic patterns are much more irregular, and less easily explained. One should note that, because of steep slopes, cliffs, and ravines, most of these islands present major topographic constraints for horizontal expansion. Therefore, artificial surfaces are predominately located across the coastal lowland areas.

The results that answer the third research question are visualized in a custom-made chart called an AZRC (Altitudinal Zonation Radial Chart), a novel geographic visualization method (Rodrigues 2016d).The AZRC method unveiled the altitudinal pattern of land cover across the main islands, namely the north/south dichotomy due to the windward/leeward climatic differentiation. This same climatic differentiation determines much of the natural land cover. Figure A23 shows the altitudinal pattern of São Miguel's land cover in the year 2006. São Miguel has the lowest altitude and gentlest slopes among the four main islands. The island's average slope across the geographic sectors ranges between 6° and 26°, and the ENE and SSE sectors have the steepest slopes on average. Maximum altitude reaches 1103 m ASL (i.e. Pico da Vara) in the ENE sector. This sector harbors the last significant patch of laurel forest on the island, which is protected by a natural reserve. Overall, Figure A23 reveals that the heterogeneous agricultural areas are the predominant land cover class across the altitudinal belts. As mentioned in the third chapter, the transformation of forested areas into cultivation fields, coupled with the introduction of grazing animals, were responsible in the past for the devastating effects on the ecosystems of the islands. For instance, in São Miguel the introduction of an intensive agricultural development model culminated in the disappearance of almost all the forests, as Figure A23 demonstrates. The gentler slopes relative to the other main islands are one of the reasons that, as of 2006 the island had only 27.18 percent of its landscape categorized as forests/semi-natural (Figure A8). In the mid-twentieth century, agricultural activities in São Miguel started to use mechanized means. The slope in the remaining main islands never allowed the same intensive use of mechanized agriculture. This facilitated the expansion of the agricultural areas and profoundly changed São Miguel's landscape. Fortunately, the steep slopes, cliffs, and ravines on Madeira, Gran Canaria, and Tenerife somewhat protected their fragile ecosystems from the anthropogenic impact that is found in São Miguel. Figure A23 reveals that, the agricultural land cover categories were predominant and extended up to 1000 m ASL, as of 2006. However, also as of 2006 the artificial surfaces did not stretch beyond the 0-200 m altitudinal belt, except in the WSW sector where they reached 200-400 m ASL.

Due to the intense anthropogenic impact that the natural areas endured, São Miguel's altitudinal forest limit is very irregular (Figure A23). As mentioned, the Atlantic laurel forests develop in areas with mild temperatures and high humidity. Immediately before the arrival of the first European settlers in the early fifteenth century in the Azores, "the laurel forests occupied the islands from the coast to the summit, with the exception of the highest slopes of the Pico peak (2350 m), which are too cold for this formation" (Fernández-Palacios et al. 2011: 240). In spite of the Azores archipelago having the best biogeographical conditions for the laurel forest (e.g. mild temperatures and annual precipitation > 600 mm on every island), these ecosystems were never allowed to recover because the archipelago landscape has been dominated by an agricultural land use up to today (Figure A8). Unfortunately, Figure A23 shows that, as of 2006 the forests relative proportion only surpassed 50 percent in the 400-600 NNW and 600-800 SSE altitudinal intervals. Figure A23 also identifies the grasslands that are located in the altitude of the original laurel forests and now used extensively for livestock and dairy cattle. Due to their semi-natural state, these areas are identified through scrub and/or herbaceous vegetation associations clearly identifiable in the 600-800 m and 800-1000 m altitudinal belts. The pastures are more easily distinguishable without empirical knowledge of the island landscape and represent permanent or semi-permanent intensive grazing areas at lower altitudes, used primarily for dairy cattle. As of 2006 these areas have not reached the 400-600 m altitudinal belt.

Figure A24 reveals the altitudinal pattern of Madeira's land cover in the year 2006. Maximum altitude reaches 1862 m ASL (i.e. Pico Ruivo) in the ENE sector. Madeira has the steepest slopes on average among the study areas. The average slope across the geographic sectors ranges between 10° and 35°, and the NNW, NNE, and ENE geographic sectors have the steepest slopes on average. As mentioned, the trade winds transport moist oceanic air masses that, when facing the island's steep windward northern slopes, condensate after a forced upward movement lowers the air temperature to its dew point. Nonetheless, normally, the resulting clouds do not have a high vertical development because of the large-scale subsidence and sinking motion of air in the High system. However, even when not producing rain, these cloudbanks are responsible for precipitation in the form of mist and fog, thus carrying the water that allows the evergreen forest to thrive. Therefore, a wetter climate prevails on the windward side than on the leeward side, as moisture is removed by orographic precipitation. Figure A24 reveals that in both the windward NNW and NNE sectors, forests start at the 0-200 altitudinal interval, reaching 1600-1800 m ASL in the NNW sector, which has the majority of its slopes with a northeasterly aspect (i.e. Madeira's windward side).

In Madeira shrub and herbaceous vegetation occur above the limit for the evergreen forest. These dryer places altitudinally above the cloud layer are characterized by a heathland with open, low-growing, woody vegetation. Figure A24 reveals that this shrub and herbaceous vegetation dominates at altitudes above 1200 m, except in the humid windward NNW sector where forests are the prevailing land cover from 400-600 m up to 1600-1800 m ASL. At lower altitudes forest patches are interrupted by artificial surfaces and land used for agriculture purposes. This interruption is most significant in the southernmost sectors of the island where the medium-low altitudinal belts have been extensively deforested (Figure A24). In the northern sectors the very steep slopes have constrained the artificial surfaces altitudinal limit to a maximum of 600-800 m ASL. In contrast, in the southern sectors the artificial altitudinal limit reaches 1000-1200 m ASL in the ESE sector, which Figure A24 shows has gentler slopes never exceeding 23° on average. Figure A24 also shows the maximum altitude reached by land cover devoted to agricultural activities. In order to have agricultural land on steep mountainous slopes, the people of the island have extensively used cultivation terraces. These terraces made agriculture possible on sloped and mountainous land. Consequently, Figure A24 shows that in the WNW sector agricultural activities reached up to 1200-1400 m ASL as of 2006.

Figure A25 reveals the altitudinal pattern of Gran Canaria's land cover for the year 2006. Maximum altitude reaches 1949 m ASL (i.e. Pico de las Nieves) in the ENE sector. The island's average slope across the geographic sectors ranges between 7° and 31°, with several geographic sectors presenting the steepest slopes on average. Regional climate in the Canaries is also determined by the Azores high-pressure system, which is responsible for the northerly and northeasterly trade winds. Consequently, a wetter climate making the northwestern slopes cooler prevails on the windward side, while the leeward southern slopes are warmer and dryer. Contrary to the Azores and Madeira where the laurel forests completely covered the islands, because of the dryer climate in the Canary Islands, the climate conditions desired by the laurel forest are best found in the windward mid-altitudes of the mountainous islands (Fernández-Palacios et al. 2011). This restricted the laurel forests distribution to the areas directly influenced by the cloudbanks, which are essential to the laurel forest during the dry summer months (i.e. June-August). Figure A25 shows that nowadays the presence of forests is only noticeable 800-1000 m ASL. Sadly, most of the laurel forest in Gran Canaria has disappeared and has been replaced by introduced species (Fernández-Palacios et al. 2011).

Among the four main Macaronesian islands of Portugal and Spain, Gran Canaria has the highest agricultural altudinal limit. For instance, in the ENE sector the land cover dedicated to agricultural activities reached 1800-2000 m ASL. Because of the dichotomy between the southern leeward dry areas and the northern windward slopes, the presence of agricultural land cover is visibly more dominant on the northern sectors. In some altitudinal intervals, agriculture covers more than 50 percent of the land (e.g. 600-800 NNE and 800-1000 NNE). Figure A25 also reveals the striking altitudinal limit of the artificial surfaces. Because of steep slopes on the western coastal areas, the artificial surfaces in Gran Canaria's western sectors never pass 400-600 m ASL. Due to the gentler slopes illustrated in Figure A25, the artificial altitudinal limit ascends to 800-1000 m in the NNE and ENE sectors.

Lastly, Figure A26 shows the altitudinal pattern of Tenerife's land cover for the year 2006. Tenerife has the highest island peak among the Macaronesian islands that is furthermore, one of the highest in the world. Maximum altitude reaches 3718 m ASL (i.e. Mount Teide) in the WSW sector. Tenerife average slope across the geographic sectors ranges between 6° and 31° with the WSW and ENE geographic sectors having the steepest slopes on average. Similar to the mountainous Canary Islands, Tenerife's laurel forest is mainly found in the mid-altitudes where wind exposure and mountain peaks are prominent factors allowing for the development of a cloud layer at about 1000 m ASL. Altitudinally above the laurel forest ecosystem is a pine forest belt, followed by heathlands. At higher altitudes there is frost and snow in the winter months (i.e. December-February), the vegetation consists of summit scrub that, as the altitudinal gradient increases, gives way to open spaces with little or no vegetation. Generally, the presence of forest belts starts to increase around 1000 m ASL, up to the range of 1400-2000 m ASL, while declining thereafter, which indicates that this altitudinal range supports the forest's optimum distribution. Figure A26 also reveals that areas above 2400 m ASL have no forest and scrubs decline sharply thereafter, a decrease typical for altitudinal gradients.

From Figure A26 one can observe that human activities are constrained below 1000 m ASL. However, Figure A26 also shows an exception, Tenerife's SSW sector where the altitudinal limits for agricultural areas and artificial surfaces has reached up to 1400-1600 ASL. Additionally, the altitudinal limits for the areas covered by artificial and agricultural areas peak in the NNW, NNE, and ENE sectors within the 0-1000 m altitudinal range. This demonstrates that the climatic conditions have influenced the location of settlements as well. Settlements were almost exclusively dependent on agricultural activities until the mid-twentieth century when tourism-related activities slowly started to dominate the island's economic activity. Expectedly, agricultural and artificial land cover proportions are more prevalent in the windward NNW and NNE sectors where orographically induced adiabatic cooling leads to the development of a cloud belt. This cloud belt provides humid conditions more favorable to agricultural land cover compared with the dry leeward southern slopes.

5.2.4. Fourth research question

What is the contemporary pattern of land development pressure on the main islands?

For the fourth research question, a novel modeling approach was proposed using land change in and into artificial surfaces as a proxy of land development pressure (Rodrigues 2016b). The results indicate that between 1990 and 2006 most of the land development pressure had not occurred in or near the main cities, but rather in smaller settlements mostly concentrated on the southern coastal areas. An important finding comes from Madeira. Despite having over half a million habitants less than Tenerife, both these islands shared a similar gradient of land development pressure. The deduced land development patterns are even more important when one considers that, between 1990 and 2006 Tenerife had a population density increase of 112 inhab./km^2, while the island of Madeira registered an increase of only 9 inhab./km^2 in the same period (Table 9). Thus, the importance that tourism and real estate speculation had on Madeira's land development is manifest.

The published article (Rodrigues 2016b) provides information about the spatial patterns of land development pressure and is the basis for answering the research question stated above. Therefore, to avoid the redundancy of transcribing the findings here, the reader should consult the provided article. Overall, the findings corroborate other researchers by associating land development pressure with tourism development and related infrastructure predominately located in the warmer, sunny, leeward southern coastal areas. Since the mid-twentieth century, parts of the north and inland populations of Gran Canaria and Tenerife began migrating to the south. This was the result of the tourism model, which attracted people from the north and inland towards the coastal southern areas. Consequently, in the Canaries there has been an internal adjustment of the population because of economic changes. This process has not occurred in Madeira because its tourism-related activity remained located in the southern city of Funchal. However, the empirical analysis highlights that, even on the islands with the greatest demographic shifts, the increase in artificial surfaces has exceeded the corresponding population growth by more than six times according to data from CEUS (2012).

It is important to realize that, in the last decades tourism-related infrastructure, major improvements in road networks and real estate speculation became the major driving forces behind land change in these islands. Because of steep slopes, cliffs, and ravines, these islands present major topographic constraints for horizontal expansion. Consequently, there is considerably less sprawl in comparison with other newly settled regions dependent on the automobile. Nonetheless, the same major topographic constrains are making territorial occupation progressively more fragmented. This fragmentation increases costs of infrastructure and road networks and affects both large and small islands impose a replication of investment. Although a replication of investment is oftentimes difficult to justify given the existing infrastructure on some islands, it may be mandatory for social equity reasons.

5.2.5. Fifth research question

How strong is the relationship between settlement patterns and the terrain on the main islands?

With the previous research questions the results have demonstrated that the islands' anthropogenic LULC patterns are not uniform and strong asymmetries exist on the islands. Moreover, there is a strong influence from physical attributes, namely distance to the coastline, altitude, and slope. Hence, after providing a methodological basis for the classification of settlement patterns (Rodrigues 2015), the last research question concludes the research by testing if the physical landscapes have a significant role in settlement patterns across these islands. In order to accept the hypothesis that topographic variables are statistically significant factors influencing the location of settlements on these islands, the proposed settlement typology was treated as the categorically distributed dependent variable, and altitude, slope, aspect, and distance from the coastline were treated as predictors. Under these circumstances, a multinomial logistic regression was performed for each of the four main islands. The logit models predicted the probability of each settlement type occurring. The results show that the overall multinomial logistic model was found to be significantly fit ($p<0.01$) on all four main islands. By including the predictor variables and maximizing the log likelihood of the outcomes seen in the data, the "Final" model improves upon the "Intercept" model for every island. The null hypothesis of there being no difference between the model without independent variables and the model with independent variables was rejected. Thus, the existence of a relationship between the independent variables and the dependent variable was supported.

Moreover, the published article (Rodrigues 2015) reveals that the most significant terrain attributes influencing the spatial distribution of settlements patterns were found to be altitude in São Miguel and Madeira, and distance from the coastline in Gran Canaria and Tenerife. Empirical knowledge of the islands' landscapes suggests that in Gran Canaria and Tenerife there is a higher pressure for settlements to be closer to the shoreline due to tourism-related activities. The pressure is lower for São Miguel and Madeira because they do not have sandy beaches. Overall, these results demonstrated that there was no difference between the model without independent variables and the model with independent variables. Consequently, the null hypothesis was rejected and the hypothesis that topographic variables are statistically significant factors influencing the location of settlements on these islands was accepted. However, the classification accuracy rates also highlight that settlement spatial variation is explained by a set of interconnected factors not present in the applied model: agricultural potential, socio-economic order, historical and political order, etc.

5.3. Future lines of research

One of the main possible lines of further research is to continue focusing on the development of new models for graphically representing geospatial data and improving extant methods. This research field is lagging among other areas of geographical research. The analysis done throughout this research highlights the potential benefits in integrating the proposed geovisualization methods with cross-sectorial planning and management approaches. This integration would support planning and decision-making processes, such as hazard mitigation planning and environmental impact assessment. The CZC method presented in this research can be easily adapted as a visualization tool for aiding coastal zone management. Moreover, the proposed geovisualization methods can also be customized for other purposes, for example, environmental conservation and biodiversity protection.

This research provided a measurement of the contemporary rates, spatial patterns, and general characteristics of the islands' LULC patterns on a broad scale. However, further analysis of the LULC dynamics across this region also requires case studies on a local scale. For example, Madeira's densely populated southern coasts and Tenerife's southern tourist center are two areas that could provide insight into very marked LULC dynamics. Local analyses would provide new understandings about the local-scale dynamics on the islands. The focus on these two areas would be particularly important for devising detailed explanatory driving forces for the region. In addition, subsequent studies should take into account more variables in order to integrate socioeconomic, demographic, and environmental data. By doing so researchers could test dynamic process models assessing the impacts that changes in land use have on societies and ecosystems.

Another possible line of research may be integrating geovisualization approaches with other spatial modeling approaches. In fact, there has been a continuous increase in the dissemination of spatial analysis methods combining approaches from GIS with other fields such as cellular automata, heuristics, decision trees, fuzzy set theory, and artificial neural networks (Triantakonstantis et al. 2011). Because of the growing importance that LULC changes have on sustainable development, large amounts of models that study LULC dynamics and simulate changes have appeared (Triantakonstantis 2012). The majority of these models simulate land category changes for a given period of time (Pontius et al. 2008). Therefore, a possible line of future research may be treating the islands' LULC data as a time-series problem. In time-series problems the objective is to predict the value of a variable by using previous values of that variable (Bishop 1995). As of 2016 CLC data for the year 2012 is being prepared. When released, this will allow researchers to have four snapshots of the islands' landscape over a period of 22 years. This will allow further modeling of LULC data, which will help establish functional relationships between a set of spatial predictor variables used to predict future change on the islands' landscape.

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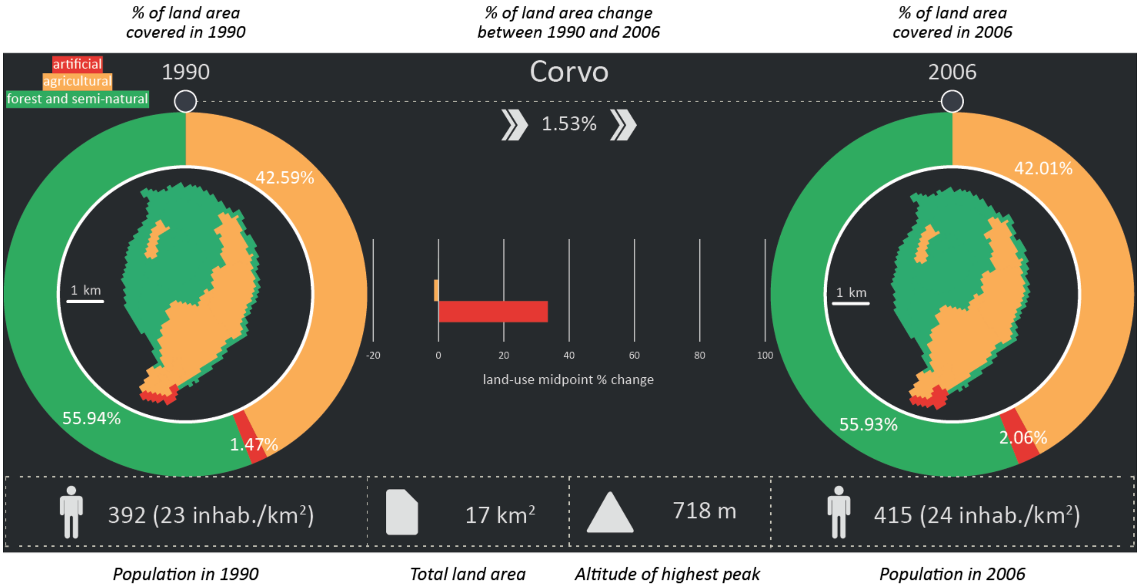
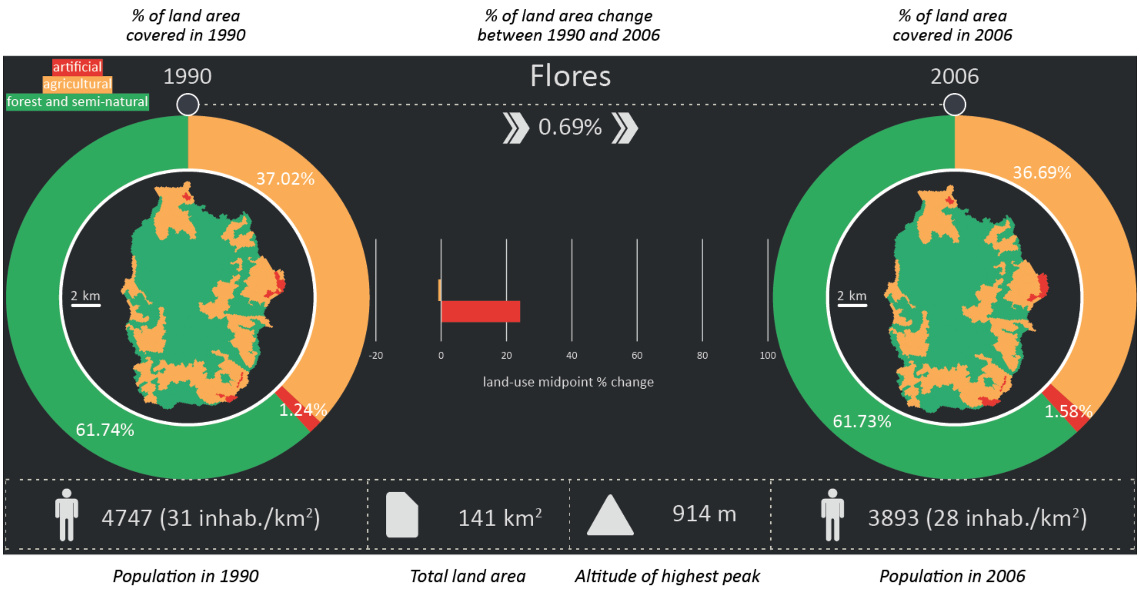
Appendix

Figure A1. Corvo's land use in 1990 and 2006.



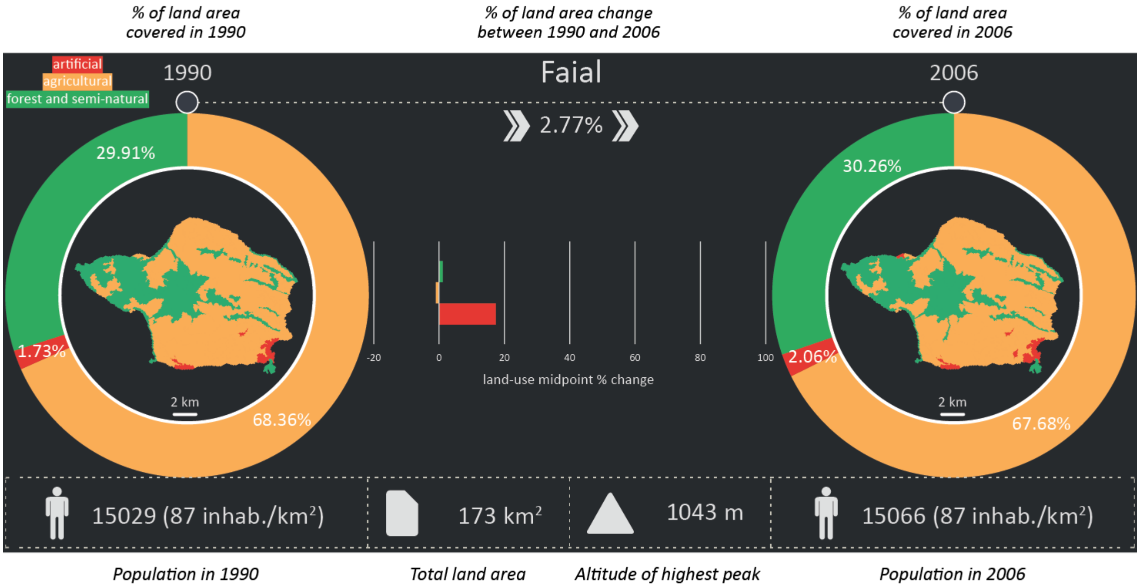
Source: Author's original (Rodrigues 2016c), using CLC1990 & CLC2006 (http://www.eea.europa.eu/data-and-maps) as data. The demographic and physical data were obtained from Instituto Nacional de Estatística (http://www.ine.pt) & Instituto Canario de Estadística (http://www.gobiernodecanarias.org/istac).

Figure A2. Flores' land use in 1990 and 2006.



Source: Author's original (Rodrigues 2016c), using CLC1990 & CLC2006 (http://www.eea.europa.eu/data-and-maps) as data. The demographic and physical data were obtained from Instituto Nacional de Estatística (http://www.ine.pt) & Instituto Canario de Estadística (http://www.gobiernodecanarias.org/istac).

Figure A3. Faial's land use in 1990 and 2006.

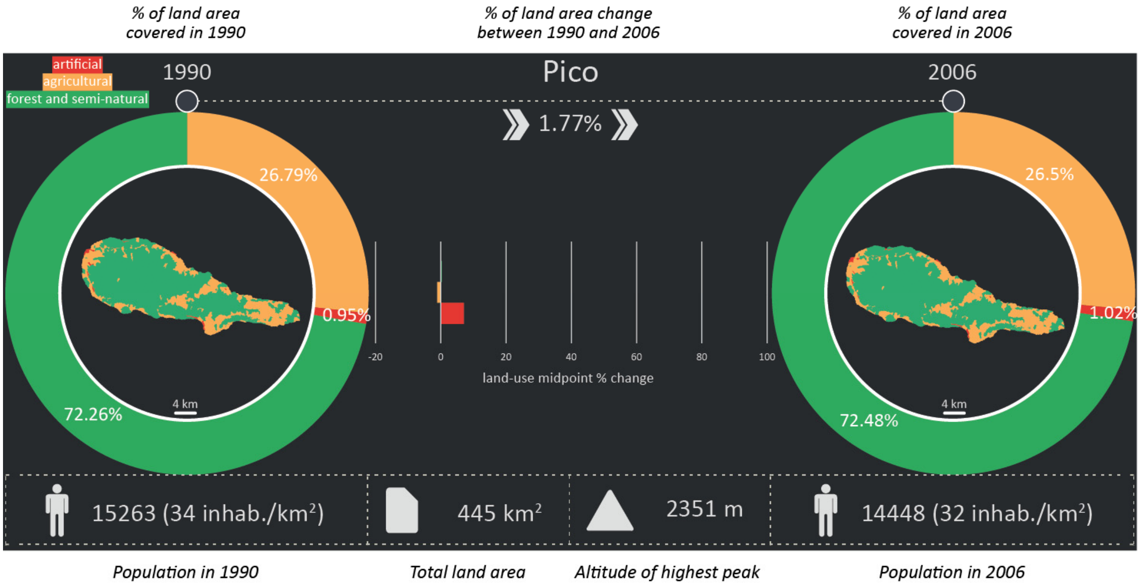


Source: Author's original (Rodrigues 2016c), using CLC1990 & CLC2006 (http://www.eea.europa.eu/data-and-maps) as data. The demographic and physical data were obtained from Instituto Nacional de Estatística (http://www.ine.pt) & Instituto Canario de Estadística (http://www.gobiernodecanarias.org/istac).

Figure A4. Graciosa's land use in 1990 and 2006.

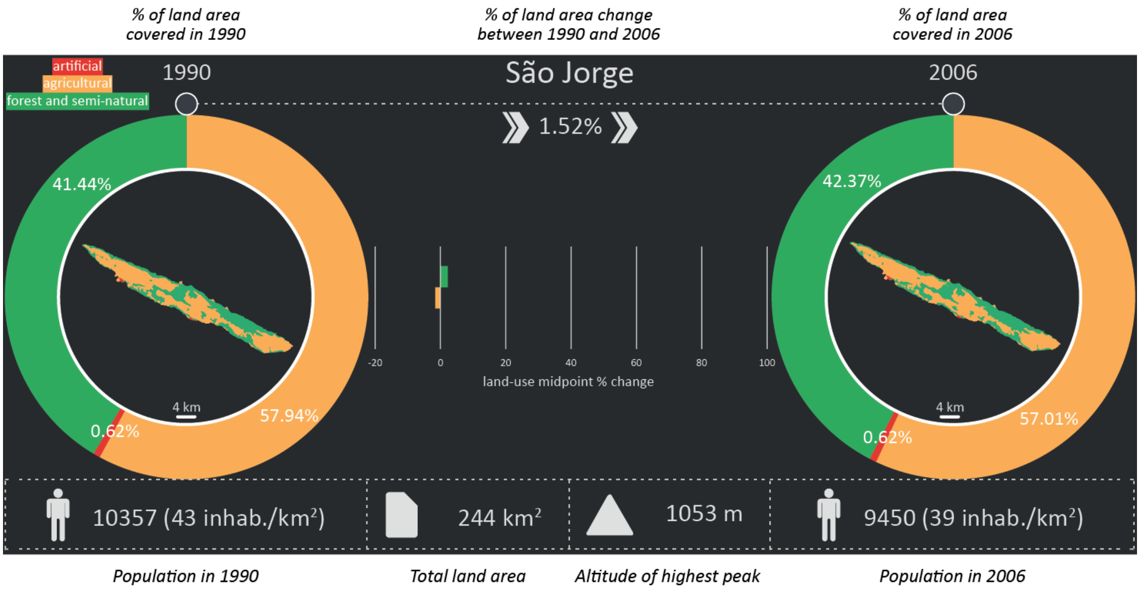
Source: Author's original (Rodrigues 2016c), using CLC1990 & CLC2006 (http://www.eea.europa.eu/data-and-maps) as data. The demographic and physical data were obtained from Instituto Nacional de Estatística (http://www.ine.pt) & Instituto Canario de Estadística (http://www.gobiernodecanarias.org/istac).

Figure A5. Pico's land use in 1990 and 2006.



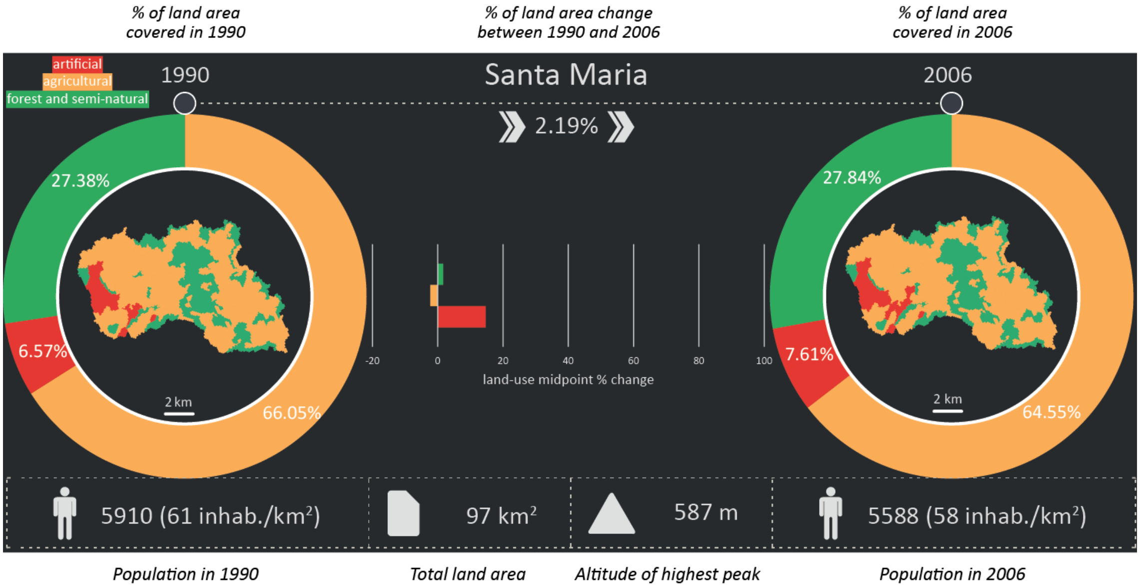
Source: Author's original (Rodrigues 2016c), using CLC1990 & CLC2006 (http://www.eea.europa.eu/data-and-maps) as data. The demographic and physical data were obtained from Instituto Nacional de Estatística (http://www.ine.pt) & Instituto Canario de Estadística (http://www.gobiernodecanarias.org/istac).

Figure A6. São Jorge's land use in 1990 and 2006.



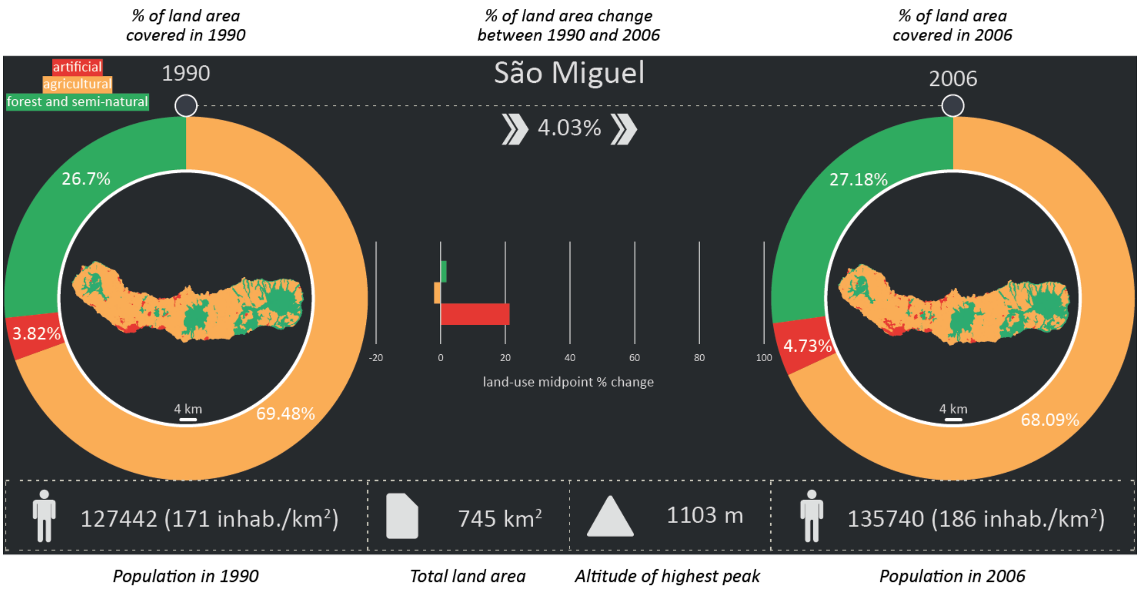
Source: Author's original (Rodrigues 2016c), using CLC1990 & CLC2006 (http://www.eea.europa.eu/data-and-maps) as data. The demographic and physical data were obtained from Instituto Nacional de Estatística (http://www.ine.pt) & Instituto Canario de Estadística (http://www.gobiernodecanarias.org/istac).

Figure A7. Santa Maria's land use in 1990 and 2006.



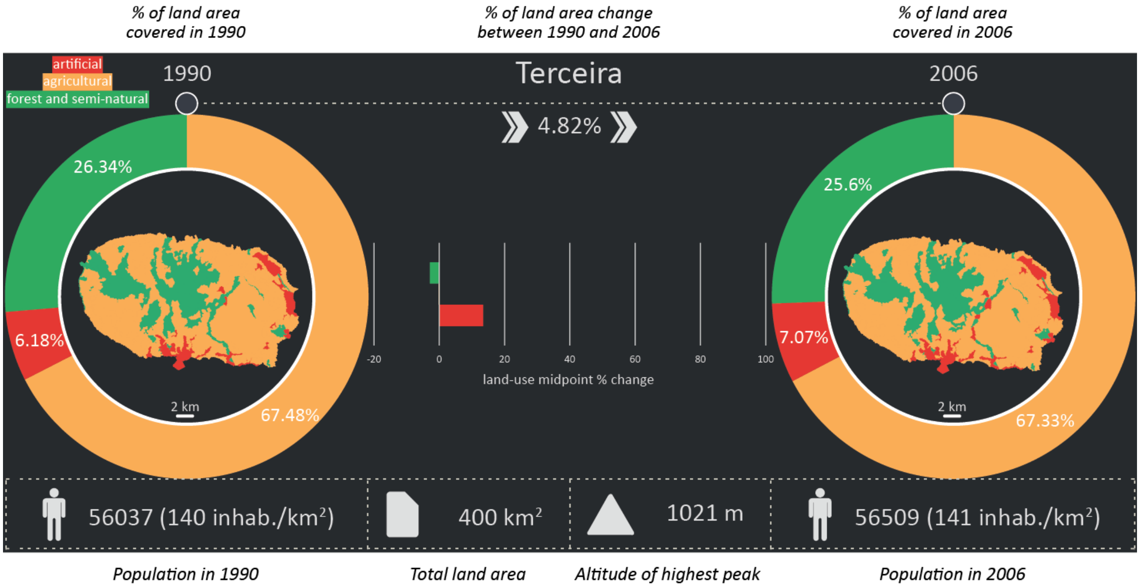
Source: Author's original (Rodrigues 2016c), using CLC1990 & CLC2006 (http://www.eea.europa.eu/data-and-maps) as data. The demographic and physical data were obtained from Instituto Nacional de Estatística (http://www.ine.pt) & Instituto Canario de Estadística (http://www.gobiernodecanarias.org/istac).

Figure A8. São Miguel's land use in 1990 and 2006.



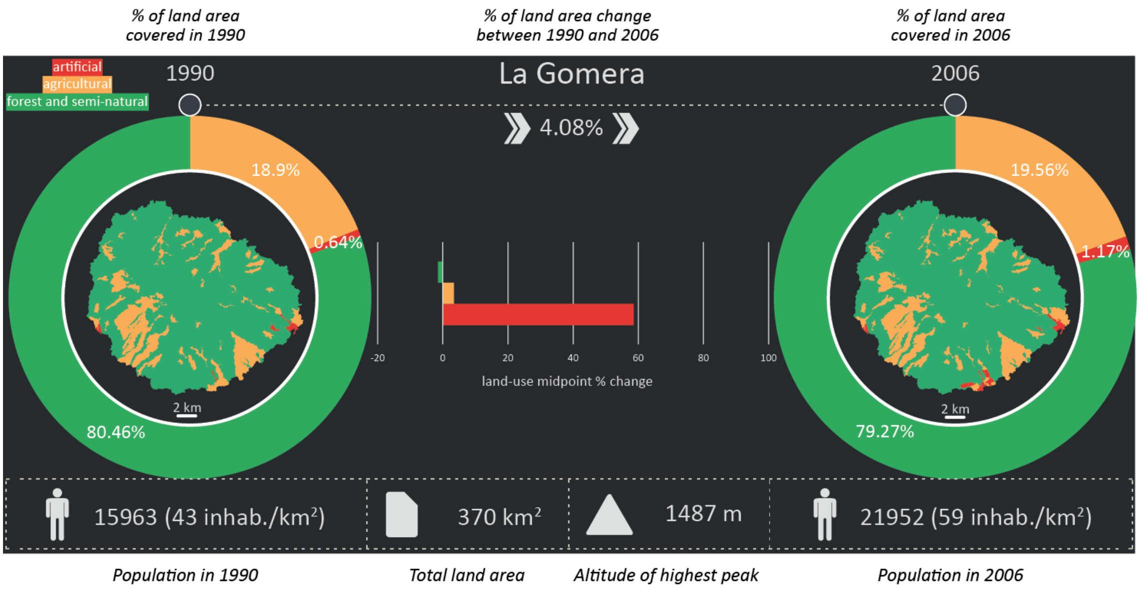
Source: Author's original (Rodrigues 2016c), using CLC1990 & CLC2006 (http://www.eea.europa.eu/data-and-maps) as data. The demographic and physical data were obtained from Instituto Nacional de Estatística (http://www.ine.pt) & Instituto Canario de Estadística (http://www.gobiernodecanarias.org/istac).

Figure A9. Terceira's land use in 1990 and 2006.



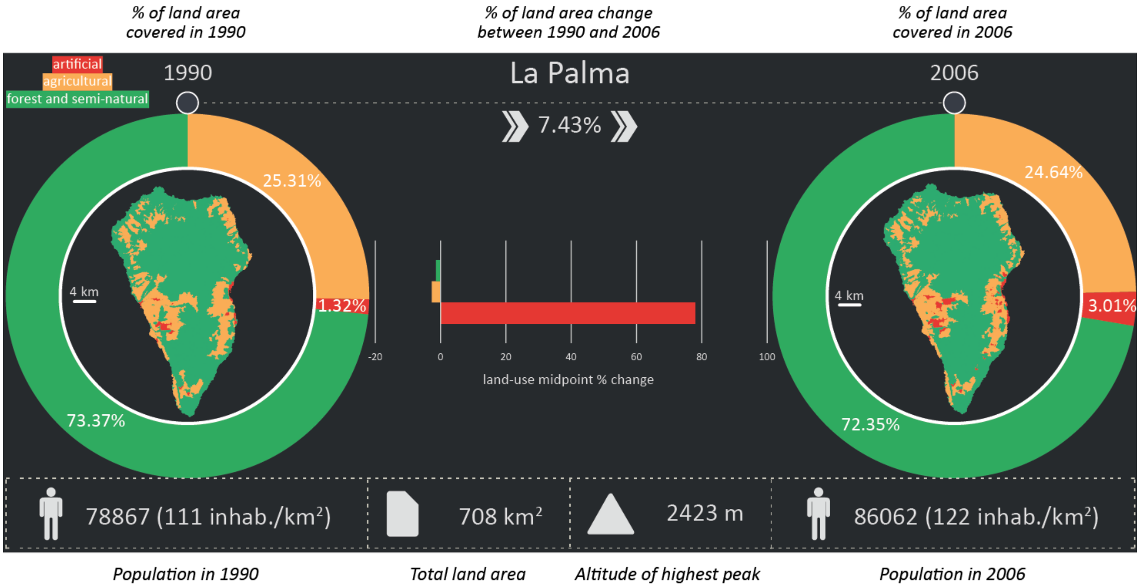
Source: Author's original (Rodrigues 2016c), using CLC1990 & CLC2006 (http://www.eea.europa.eu/data-and-maps) as data. The demographic and physical data were obtained from Instituto Nacional de Estatística (http://www.ine.pt) & Instituto Canario de Estadística (http://www.gobiernodecanarias.org/istac).

Figure A10. La Gomera's land use in 1990 and 2006.



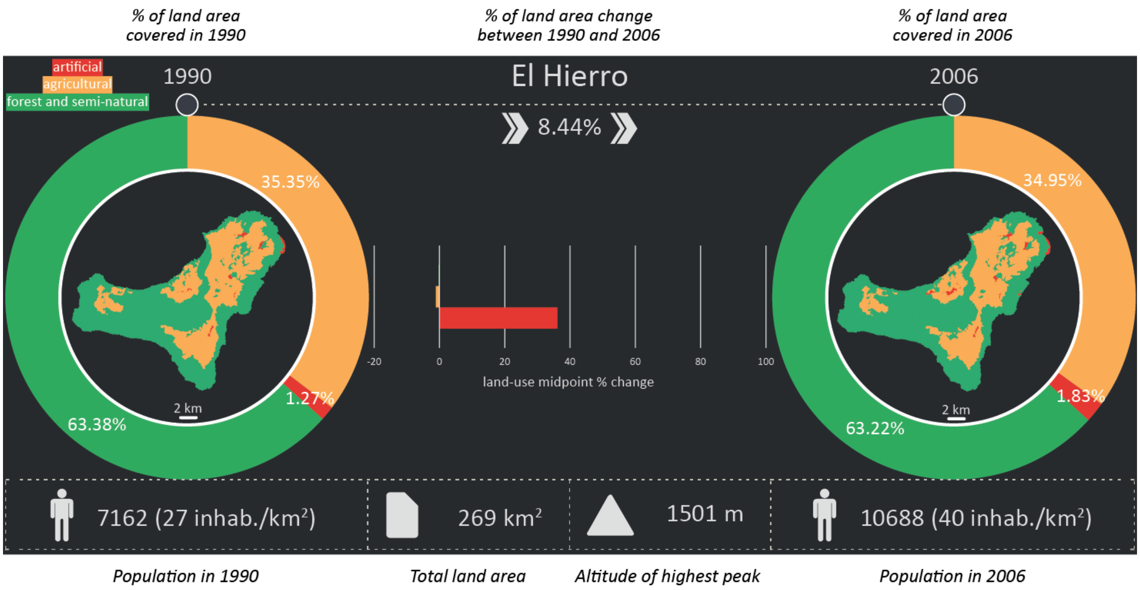
Source: Author's original (Rodrigues 2016c), using CLC1990 & CLC2006 (http://www.eea.europa.eu/data-and-maps) as data. The demographic and physical data were obtained from Instituto Nacional de Estatística (http://www.ine.pt) & Instituto Canario de Estadística (http://www.gobiernodecanarias.org/istac).

Figure A11. La Palma's land use in 1990 and 2006.



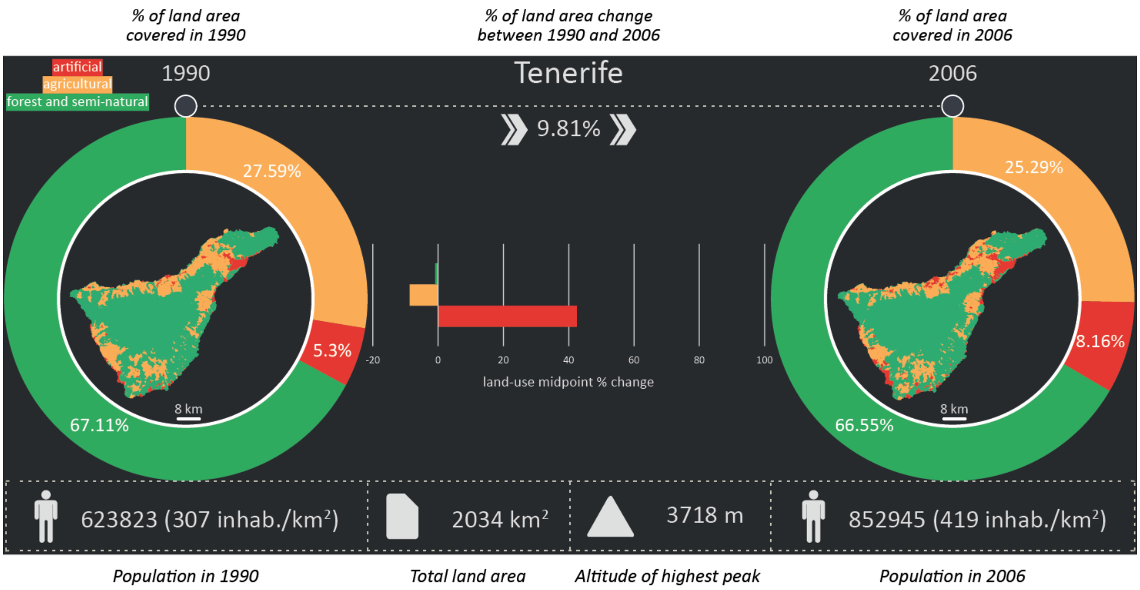
Source: Author's original (Rodrigues 2016c), using CLC1990 & CLC2006 (http://www.eea.europa.eu/data-and-maps) as data. The demographic and physical data were obtained from Instituto Nacional de Estatística (http://www.ine.pt) & Instituto Canario de Estadística (http://www.gobiernodecanarias.org/istac).

Figure A12. El Hierro's land use in 1990 and 2006.



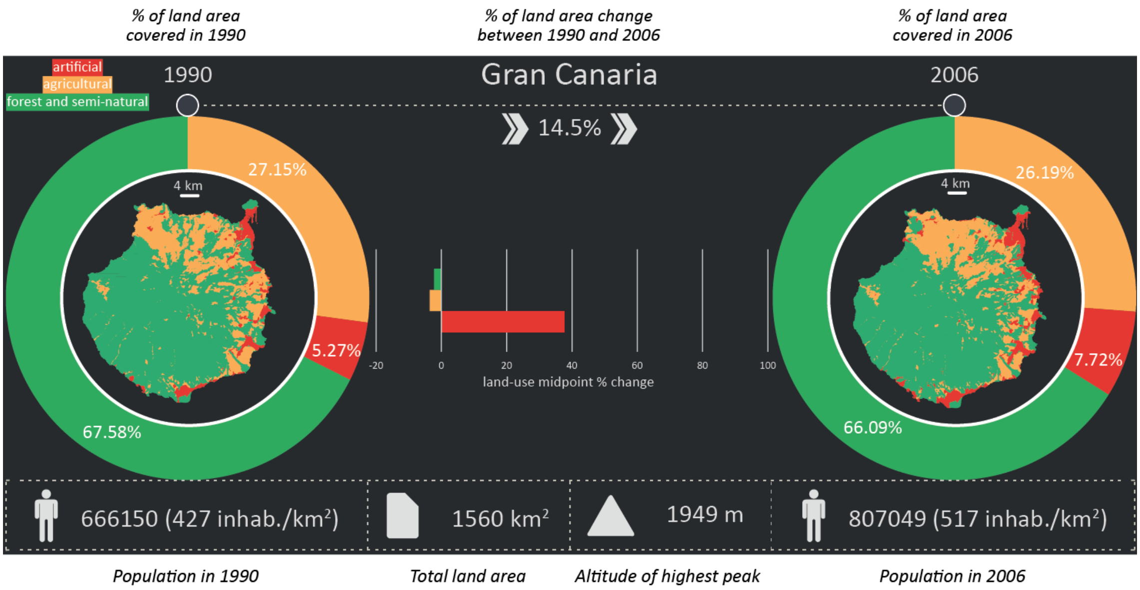
Source: Author's original (Rodrigues 2016c), using CLC1990 & CLC2006 (http://www.eea.europa.eu/data-and-maps) as data. The demographic and physical data were obtained from Instituto Nacional de Estatística (http://www.ine.pt) & Instituto Canario de Estadística (http://www.gobiernodecanarias.org/istac).

Figure A13. Tenerife's land use in 1990 and 2006.



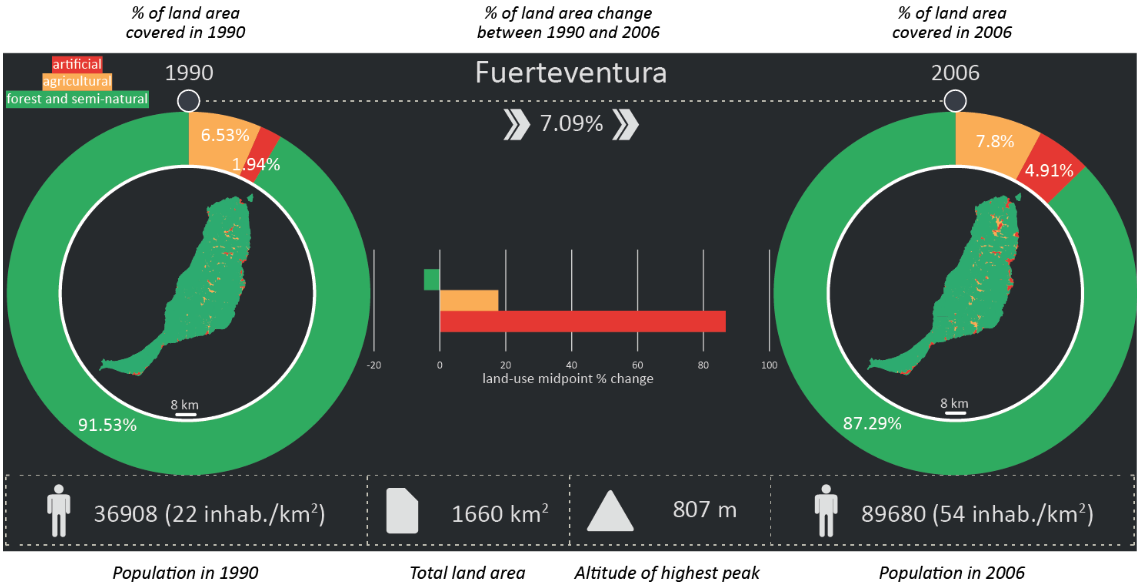
Source: Author's original (Rodrigues 2016c), using CLC1990 & CLC2006 (http://www.eea.europa.eu/data-and-maps) as data. The demographic and physical data were obtained from Instituto Nacional de Estatística (http://www.ine.pt) & Instituto Canario de Estadística (http://www.gobiernodecanarias.org/istac).

Figure A14. Gran Canaria's land use in 1990 and 2006.



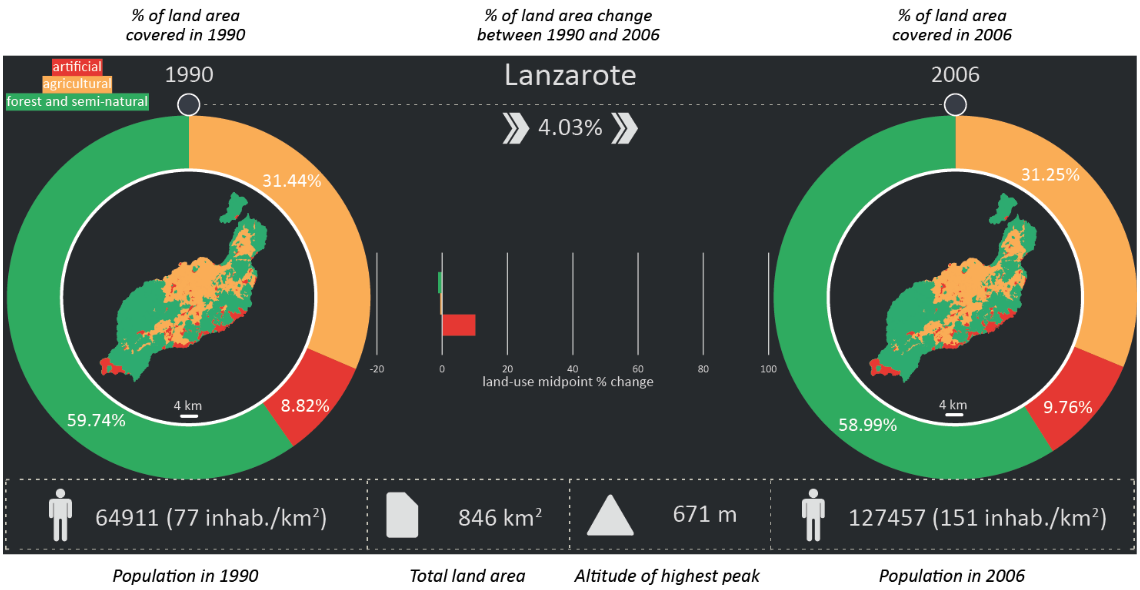
Source: Author's original (Rodrigues 2016c), using CLC1990 & CLC2006 (http://www.eea.europa.eu/data-and-maps) as data. The demographic and physical data were obtained from Instituto Nacional de Estatística (http://www.ine.pt) & Instituto Canario de Estadística (http://www.gobiernodecanarias.org/istac).

Figure A15. Fuerteventura's land use in 1990 and 2006.



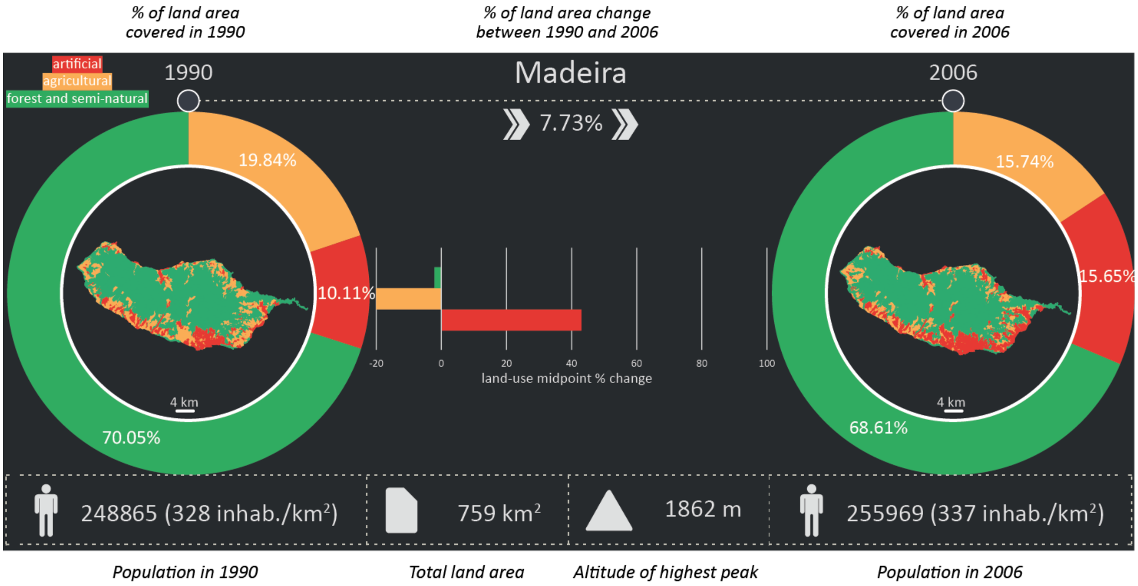
Source: Author's original (Rodrigues 2016c), using CLC1990 & CLC2006 (http://www.eea.europa.eu/data-and-maps) as data. The demographic and physical data were obtained from Instituto Nacional de Estatística (http://www.ine.pt) & Instituto Canario de Estadística (http://www.gobiernodecanarias.org/istac).

Figure A16. Lanzarote's land use in 1990 and 2006.



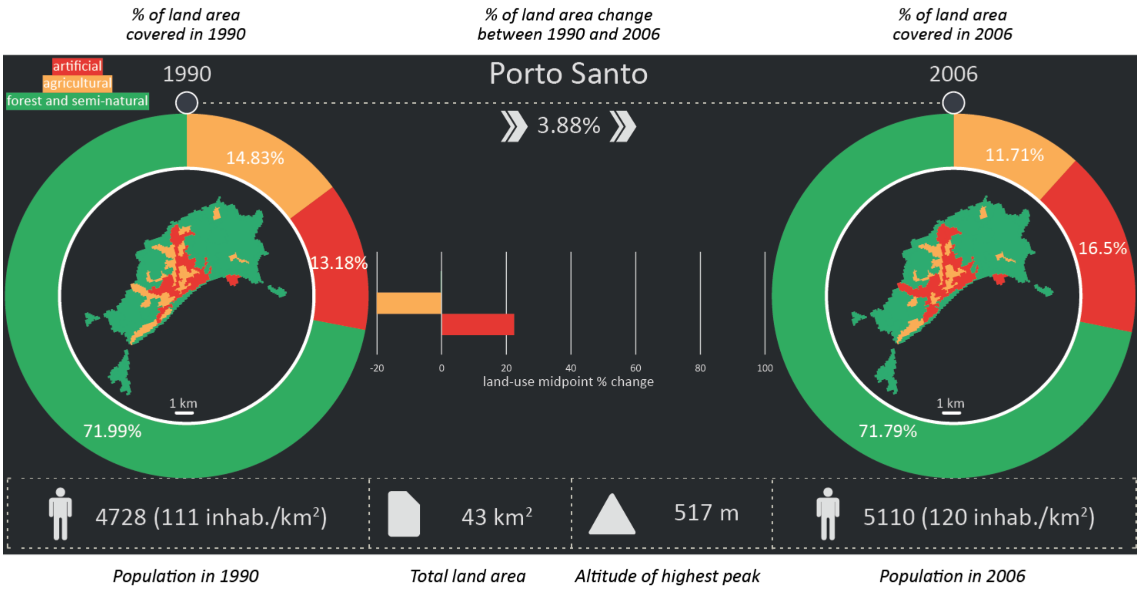
Source: Author's original (Rodrigues 2016c), using CLC1990 & CLC2006 (http://www.eea.europa.eu/data-and-maps) as data. The demographic and physical data were obtained from Instituto Nacional de Estatística (http://www.ine.pt) & Instituto Canario de Estadística (http://www.gobiernodecanarias.org/istac).

Figure A17. Madeira's land use in 1990 and 2006.



Source: Author's original (Rodrigues 2016c), using CLC1990 & CLC2006 (http://www.eea.europa.eu/data-and-maps) as data. The demographic and physical data were obtained from Instituto Nacional de Estatística (http://www.ine.pt) & Instituto Canario de Estadística (http://www.gobiernodecanarias.org/istac).

Figure A18. Porto Santo's land use in 1990 and 2006.

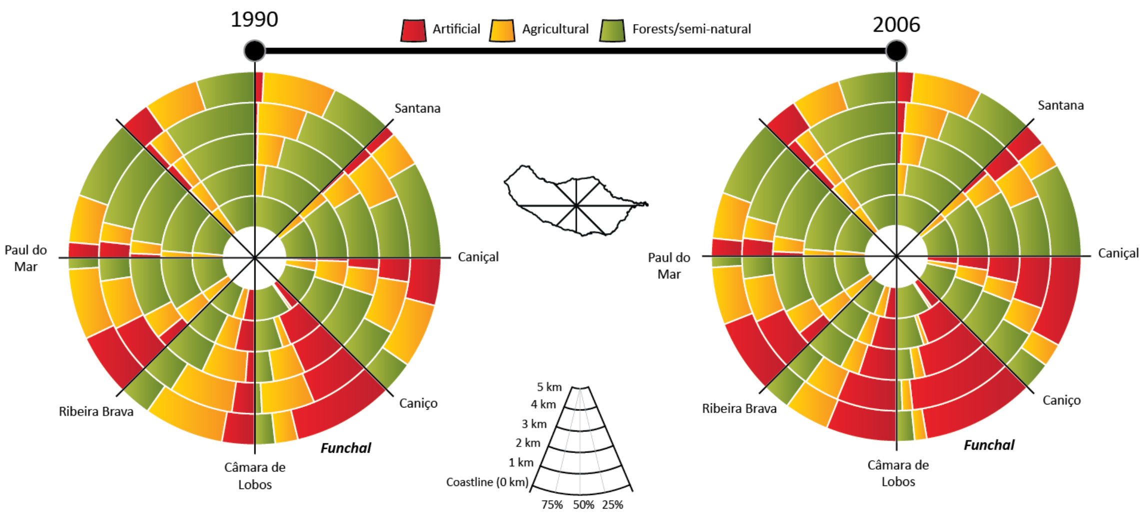


Source: Author's original (Rodrigues 2016c), using CLC1990 & CLC2006 (http://www.eea.europa.eu/data-and-maps) as data. The demographic and physical data were obtained from Instituto Nacional de Estatística (http://www.ine.pt) & Instituto Canario de Estadística (http://www.gobiernodecanarias.org/istac).

Figure A19. São Miguel's coastal land use in 1990 and 2006.

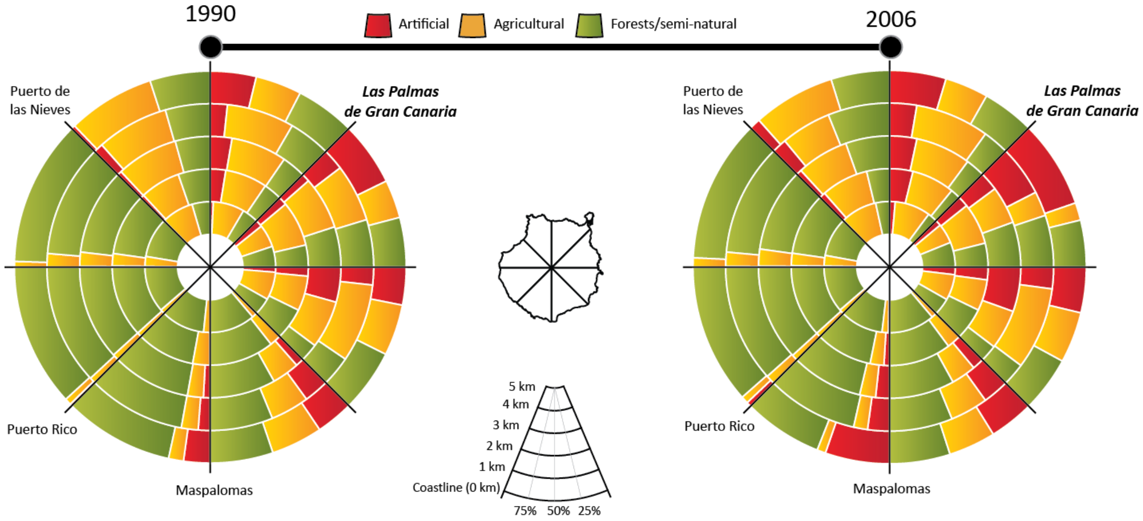
Source: Author's original using CLC1990 & CLC2006 (http://www.eea.europa.eu/data-and-maps) as data. The method is the same as presented by Rodrigues (2016).

Figure A20. Madeira's coastal land use in 1990 and 2006.



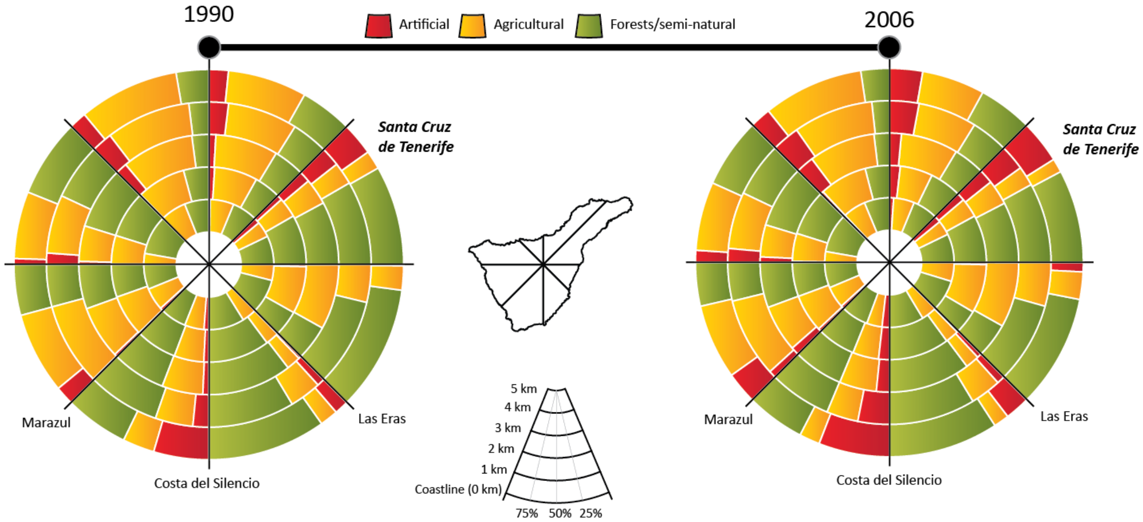
Source: Author's original using CLC1990 & CLC2006 (http://www.eea.europa.eu/data-and-maps) as data. The method is the same as presented by Rodrigues (2016).

Figure A21. Gran Canaria's coastal land use in 1990 and 2006.



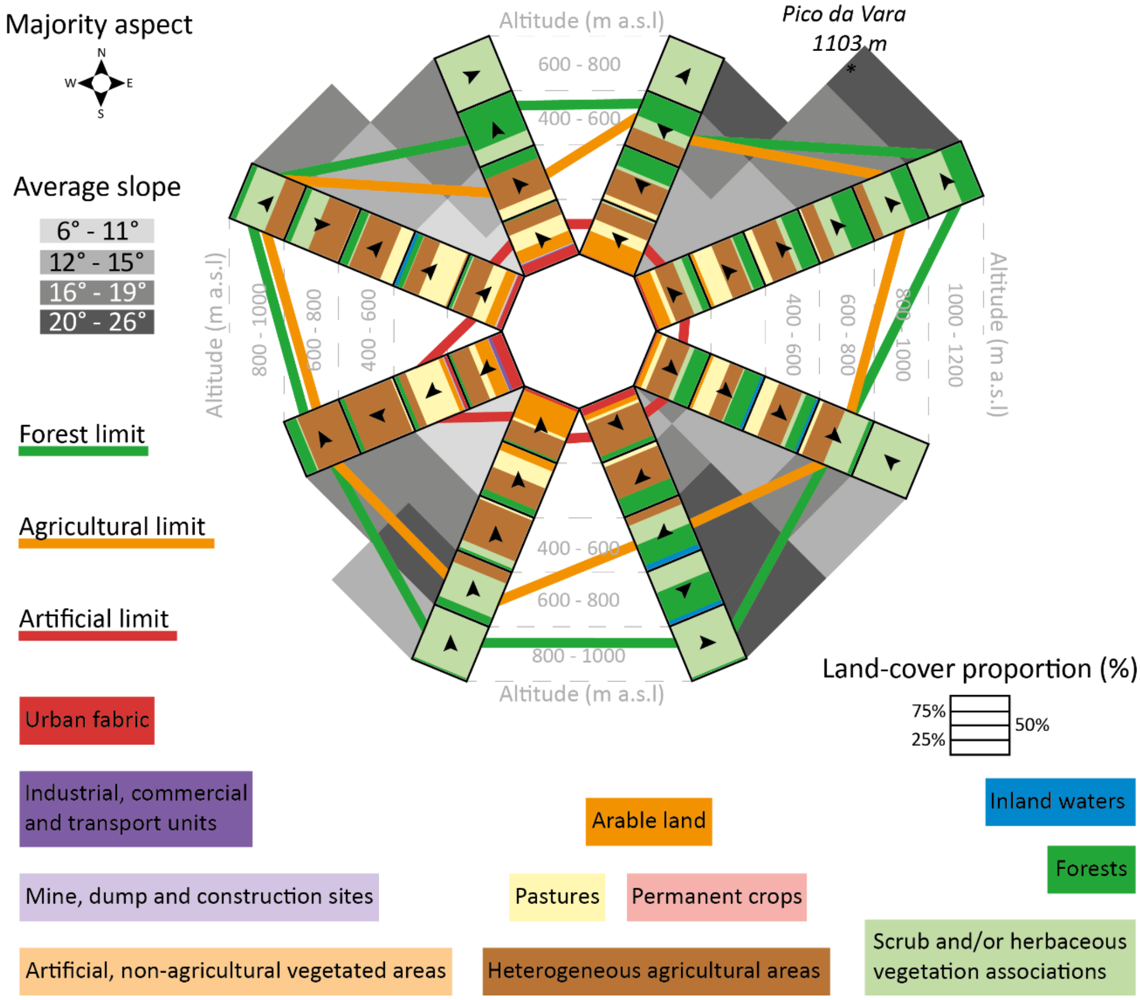
Source: Author's original using CLC1990 & CLC2006 (http://www.eea.europa.eu/data-and-maps) as data. The method is the same as presented by Rodrigues (2016).

Figure A22. Tenerife's coastal land use in 1990 and 2006.



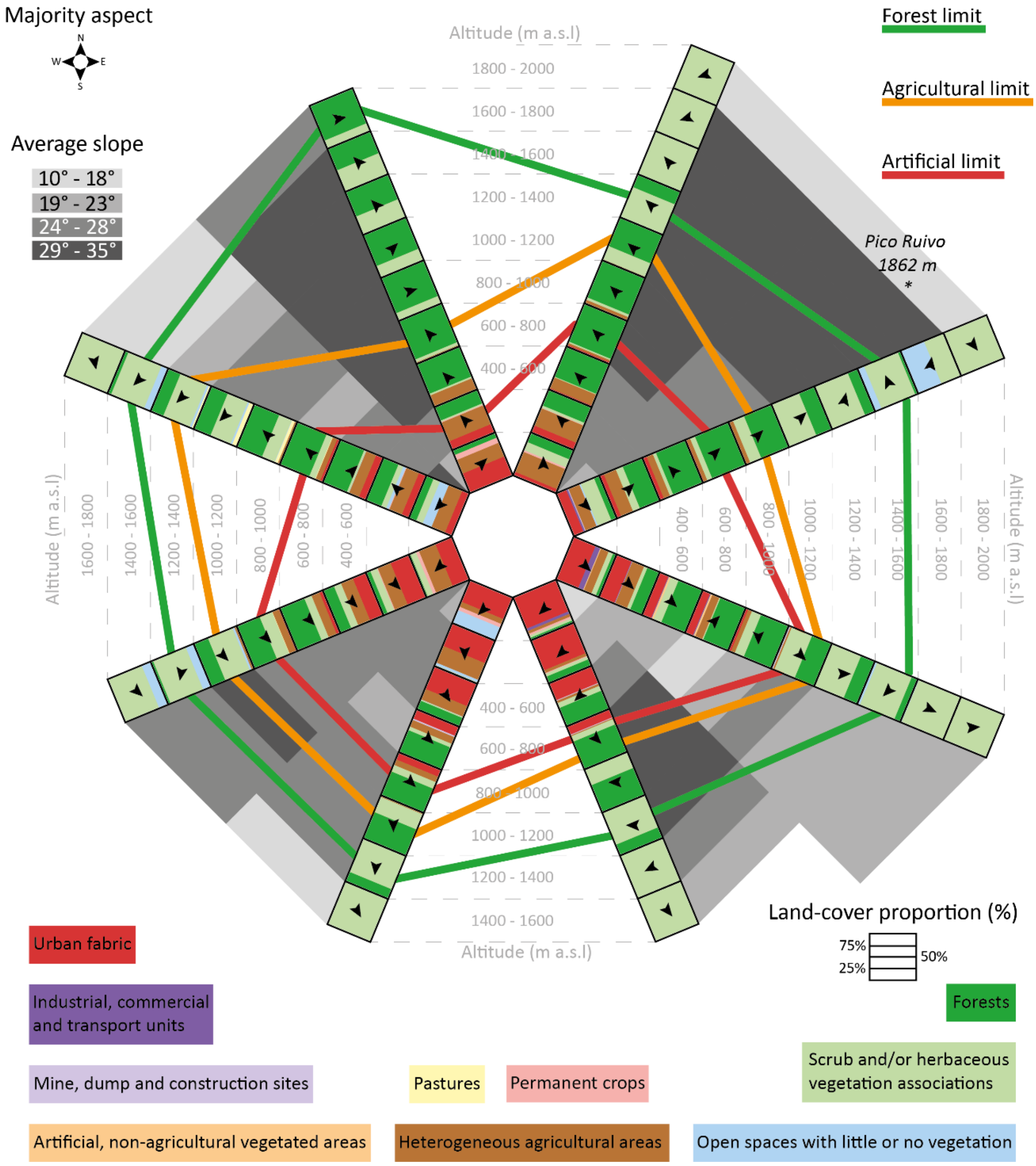
Source: Author's original using CLC1990 & CLC2006 (http://www.eea.europa.eu/data-and-maps) as data. The method is the same as presented by Rodrigues (2016).

Figure A23. Altitudinal zonation of São Miguel's land cover in 2006.



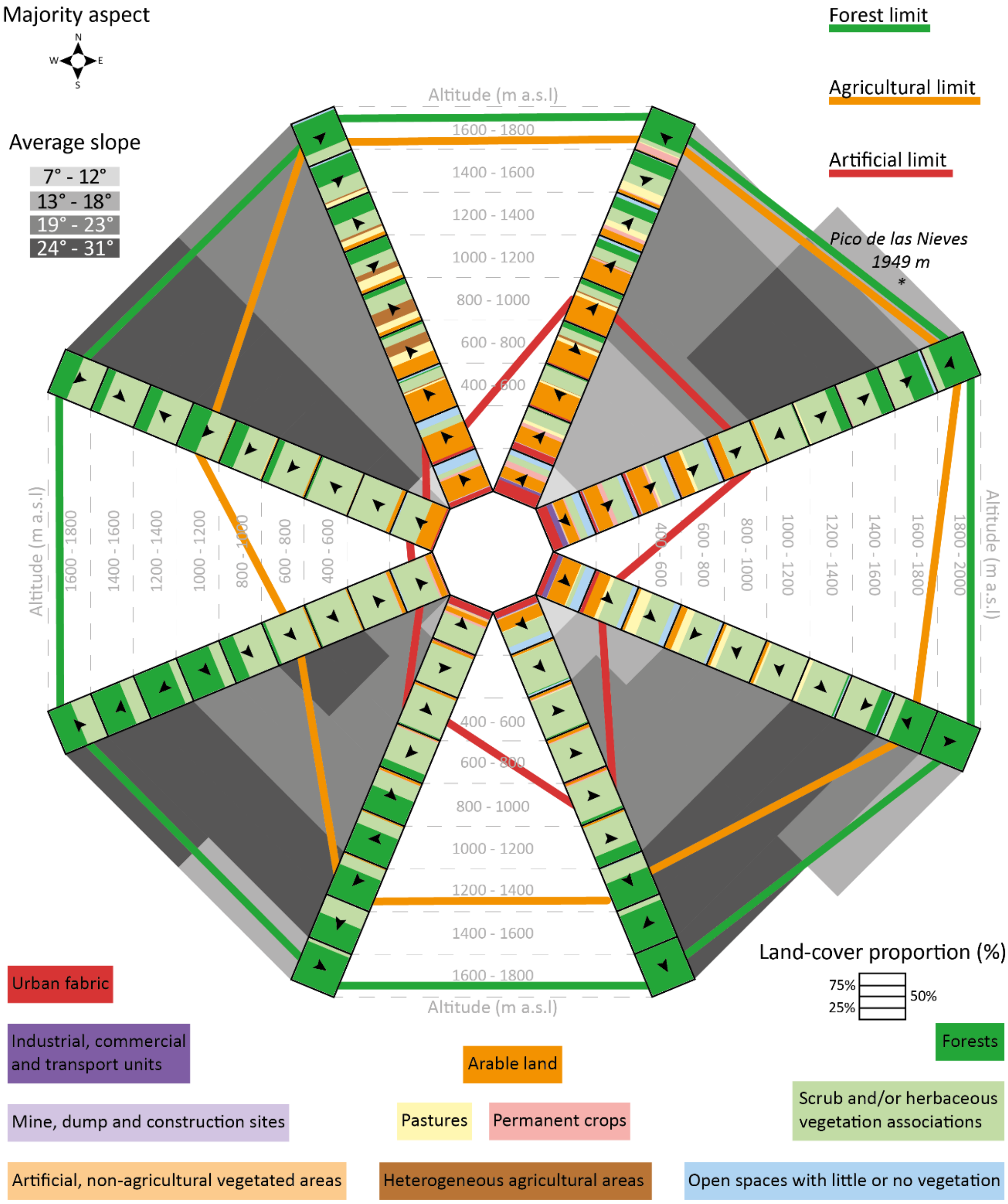
Source: Author's original (Rodrigues 2016d), using CLC2006 (http://www.eea.europa.eu/data-and-maps) & GDMED2 (http://reverb.echo.nasa.gov) as data.

Figure A24. Altitudinal zonation of Madeira's land cover in 2006.



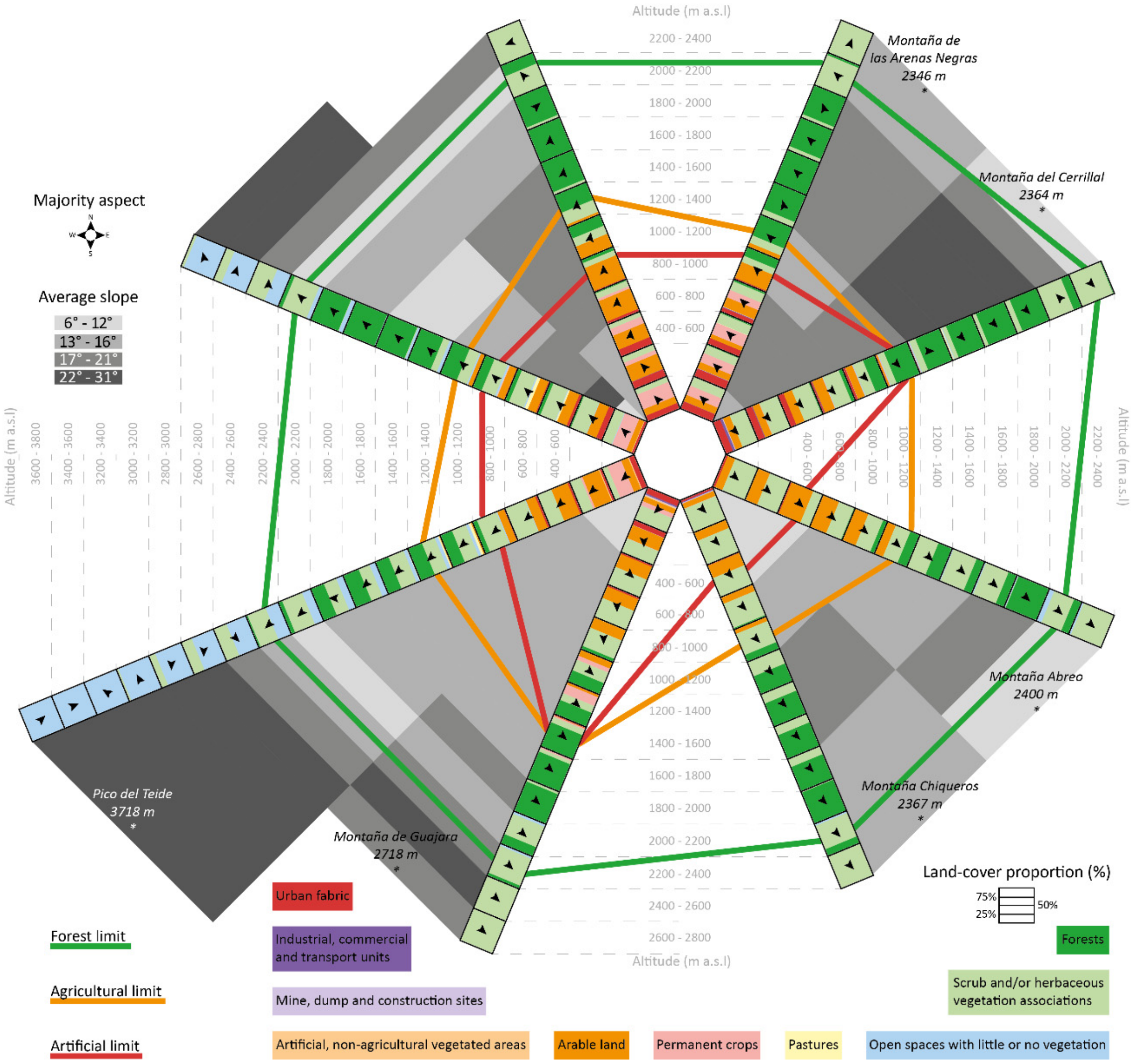
Source: Author's original (Rodrigues 2016d), using CLC2006 (http://www.eea.europa.eu/data-and-maps) & GDMED2 (http://reverb.echo.nasa.gov) as data.

Figure A25. Altitudinal zonation of Gran Canaria's land cover in 2006.



Source: Author's original (Rodrigues 2016d), using CLC2006 (http://www.eea.europa.eu/data-and-maps) & GDMED2 (http://reverb.echo.nasa.gov) as data.

Figure A26. Altitudinal zonation of Tenerife's land cover in 2006.



Source: Author's original (Rodrigues 2016d) using CLC2006 (http://www.eea.europa.eu/data-and-maps) & GDMED2 (http://reverb.echo.nasa.gov) as data.